AD-A062 790    TRW DEFENSE AND SPACE SYSTEMS GROUP REDONDO BEACH CALIF    F/G 9/1

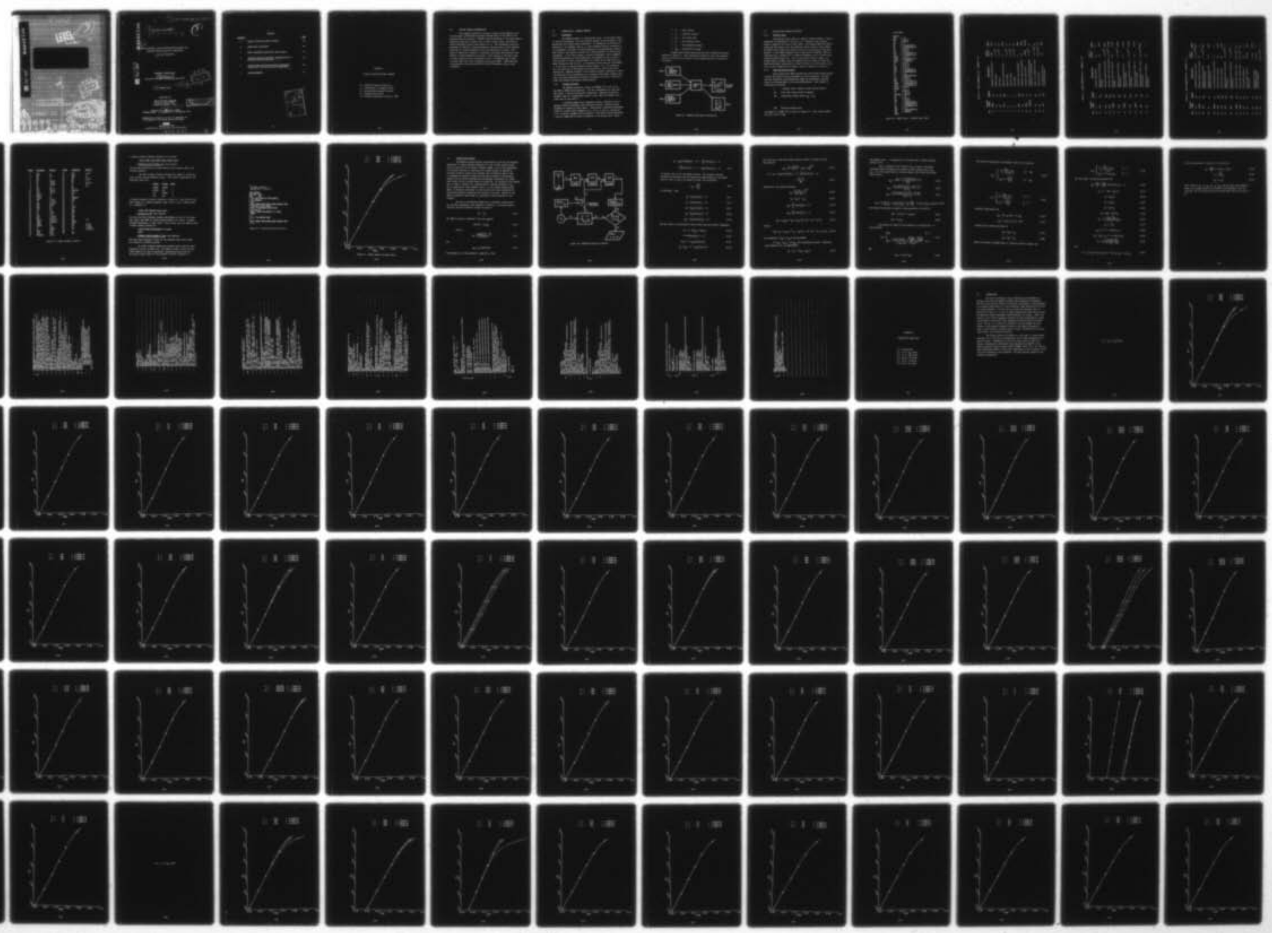
PROCESS-ORIENTED, HIGH-INJECTION CIRCUIT MODELS FOR INTEGRATED --ETC(U)

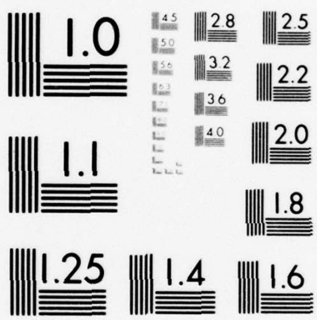
JAN 78   J CHOMA    N00014-77-C-0043

UNCLASSIFIED    TRW-78.4734.7-023-PT-2-VO    NL

1 OF 4

AD A062790





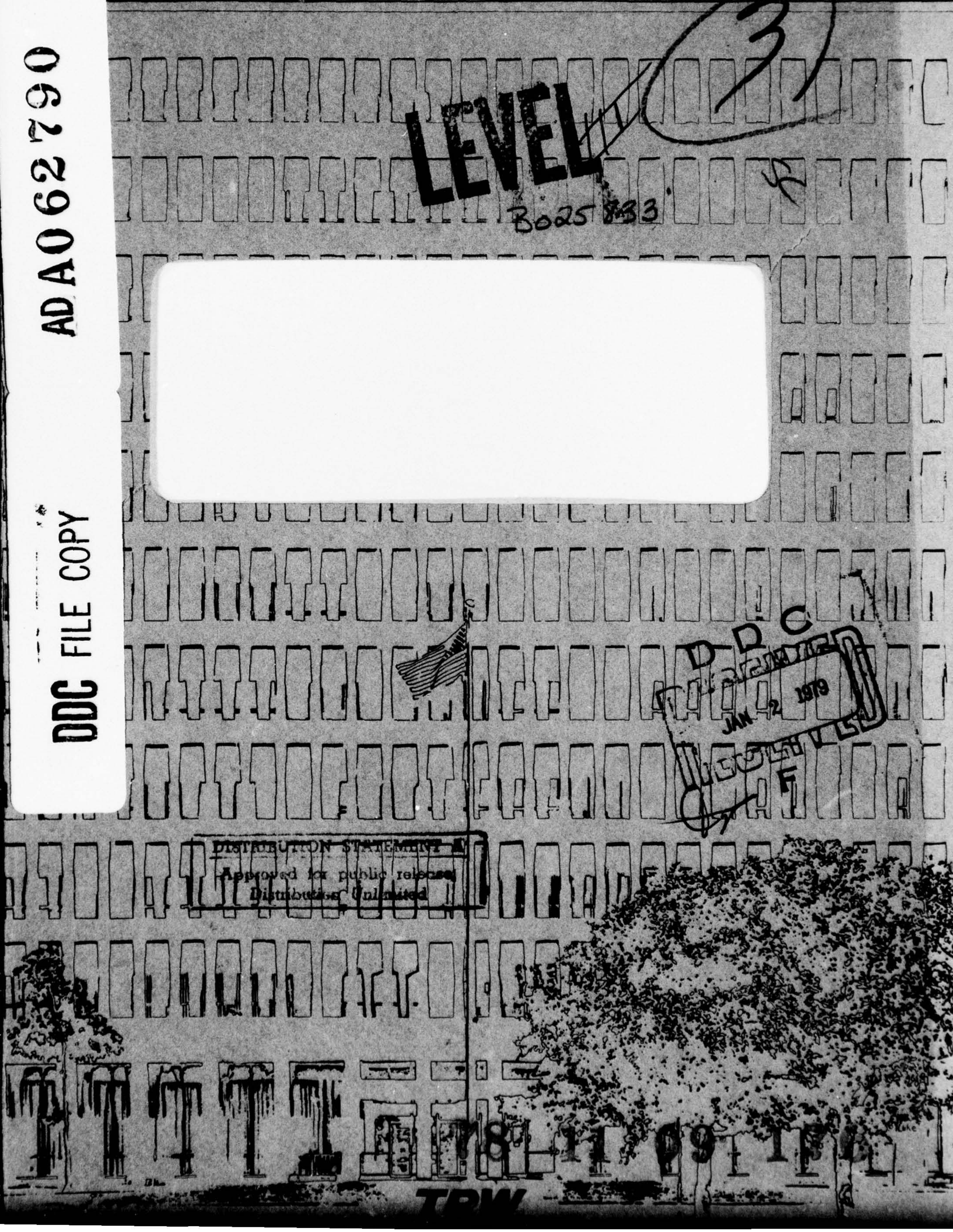

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

# TRW



LEVEL III

B025 833





DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

78 11 09 1[illegible]

TRW

Code 427
NR.

(14) TRW- 78.4734.7-023 - PT-2-VOL-2



(9) FINAL REPORT.
21 Jan 77 - 28 Feb 78

(3)

(6)

# PROCESS-ORIENTED, HIGH-INJECTION CIRCUIT MODELS FOR INTEGRATED BIPOLAR JUNCTION TRANSISTORS.

PART II. - VOLUME II.



PRINCIPAL INVESTIGATOR

(10) Dr. John Choma, Jr
Electronic Systems & Technology Department



(11) January 1978

(12) 304p.

Executed for

OFFICE OF NAVAL RESEARCH
800 North Quincy Road
Arlington, Virginia 22217



(15) Contract No.: N00014-77-C-0043
CONTRACT DATES: 21 January 1977 — 28 February 1978



TRW
DEFENSE AND SPACE SYSTEMS GROUP
ONE SPACE PARK · REDONDO BEACH · CALIFORNIA 90278



409 637

LB

CONTENTS

# APPENDIX A

## EQSOLVE (EQUATION SOLVER) PROGRAM

## A.0 EQSOLVE PROGRAM DOCUMENTATION

This appendix describes a software program called EQSOLVE, which was developed at TRW Defense and Space Systems Group for the ONR in conjunction with this contract. EQSOLVE accepts parameters of the Choma Bipolar Transistor model and a tabular list of base current values, and produces device performance curves such as Beta vs. Ic. The performance curves are presented in families, allowing parametric variation with a third parameter which may be a model parameter or the collector-emitter voltage. This allows a sensitivity analysis of transistor operating characteristics with respect to model parameters and allows a "fine tuning" of the model based on easily observed device performance curves. The EQSOLVE code is made to accept model data from a companion code called PAREV. PAREV generates from electrical and processing data the model parameters used as input to EQSOLVE.

## A.1 INTRODUCTION — PROGRAM OVERVIEW

### A.1.1 Objectives

The EQSOLVE program is a dual-purpose code. In the early stages of contract performance, the code provided insight into development of test methodology for specific model parameters. By examination of Calcomp plot families of, for example, Beta vs. $I_c$ with extrinsic emitter resistance $R_e$ as a parameter, the effect of model parameters on test-generated curves is made evident, and insight is gained into testing methods for various model parameters. In the later stages of contract performance, after parameter testing methodology has been established, the EQSOLVE is code is used to fine tune and to verify the performance of a given device model prior to model release for CAD activity. An additional future goal for the EQSOLVE is in the area of computer-assisted device design, i.e., the process of using an ideal set of performance characteristics to direct the device fabrication. EQSOLVE provides a link allowing software comparison of ideal and predicted device performance in an iterative improvement feedback loop that can produce masking and diffusion information for device fabrication based upon desired performance characteristics.

### A.1.2 Program Structure

The EQSOLVE program is written in FORTRAN IV for use on the CDC 6000 or CYBER series machines. The core requirements are less than 60K (octal) to insure interactivity capability. Expected interactive terminal time for a single graph output is less than five minutes with a total cost of less than $5.

A multiple graph output capability exists, allowing a user to generate several performance curve families on which a different model parameter is varied for every family. Additionally, different performance curves for a given model parameter (e.g., $f_T$ vs. $I_c$ with $R_c$ varying and $\beta$ vs. $I_c$ with $R_c$ varying) can be generated. Each family request generates a list of common device values in addition to the Calcomp plot, namely:

1. $I_B$ — Base current

2. $I_C$ — Collector current

3. $h_{FE}$ — DC current gain

4. $B_F$ — Base pushout factor

5. $f_T$ — Gain bandwidth product

6. $V_{BE}$ — Base-emitter voltage

Program input-output interaction and user interaction are summarized in figure A-1. User interaction consists of real time requests, wherein the details and contents of the Calcomp families of curves are stipulated.

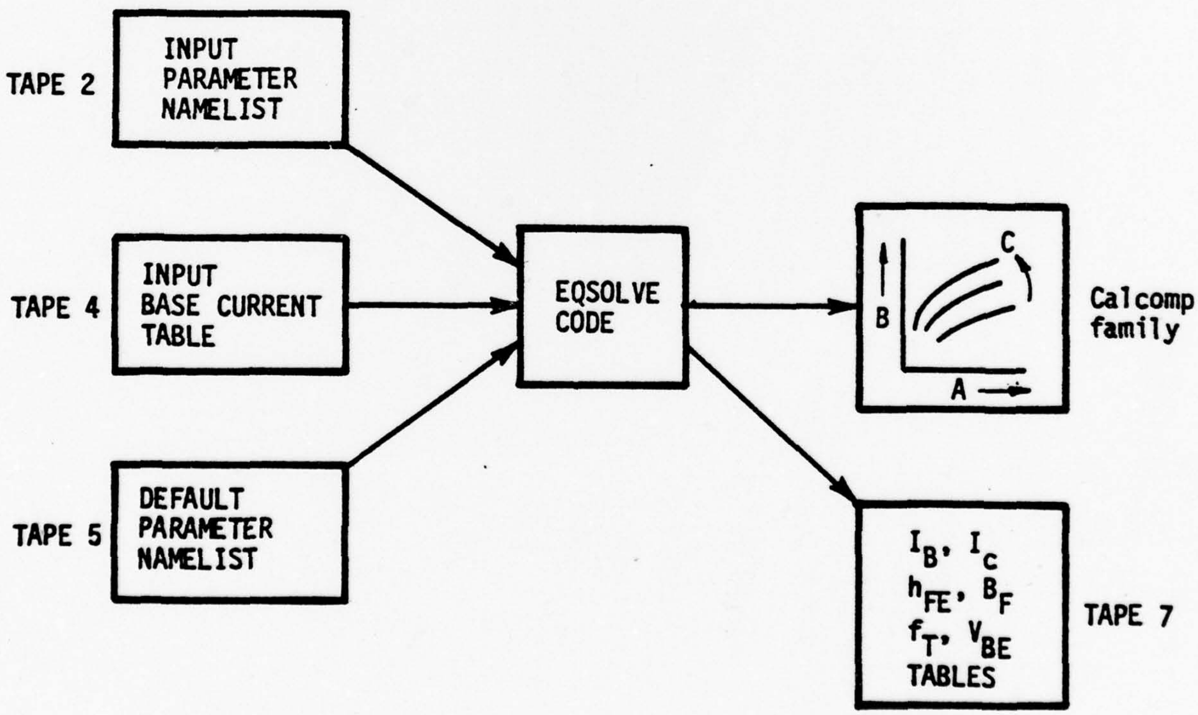



Figure A-1 EQSOLVE Input-Output Interaction

## A.2 DETAILED MAIN PROGRAM STRUCTURE

### A.2.1 Namelist Input

The namelist input works in a default override fashion. Default parameters corresponding to the model of a 2 Gigahertz small geometry bipolar transistor are used on input TAPE5. The program reads the default values and then reads in any user-supplied update values on input TAPE2. The TAPE2 values replace the default values for the duration of the user session. If the PAREV companion code is used prior to EQSOLVE, TAPE2 is available with a complete set of updated parameters, and it totally overwrites the TAPE5 default set. This is the expected mode of usage. An example TAPE2 for PAREV output and EQSOLVE input is shown in figure A-2. Detailed parameter explanation is found in Section 2 of this report, and a list of input parameters with default values is supplied in table A-1.

### A.2.2 Base Current File Input

Base current file TAPE4 contains the list of base current points at which the bipolar device performance is to be calculated. The user thus has flexibility in selecting the range and coarseness of Calcomp output by tailoring TAPE4 to his own specifications. Input format is free-format as follows:

N < integer value = number of base current points >

IB1 First base current point in amperes

IB2 Second base current point ($I_{B2} > I_{B1}$)

.

.

.

IBN Nth base current point

An example of a TAPE4 file is given in Figure A-3. Base current points are from .1μA to 1.0mA.

```
[ LIST,TAPE2

 1$TRANS
  RBO      = 1.8,
  RBB      = 1.5E+02,
  RE       = 5.0E-01,
  RCC      = 0.,
  BS       = 3.333333333E-01,
  BC       = 3.333333333E-01,
  BE       = 5.0E-01,
  CSO      = 2.0E-12,
  CEO      = 8.998858595E-13,
  CCO      = 7.999348551E-13,
  PHISS    = 9.0E-01,
  PHICO    = 9.004004474E-01,
  PHIEO    = 1.200517562,
  ISR      = 3.0E-12,
  IS       = 3.2E-16,
  IER      = 3.0E-14,
  IBR      = 3.0E-13,
  VER      = 2.196833685E+01,
  VCR      = 6.056999515E+01,
  NC       = 1.8,
  VT       = 2.587500647E-02,
  VTS      = 3.0E-02,
  QFN      = 6.178E-16,
  QRN      = 2.261411812E-12,
  TAUFO    = 1.275024046E-10,
  TAUR     = 4.667132469E-07,
  BETAO    = 5.5E+01,
  BETAR    = 1.5,
  AE       = 9.8E-07,
  XO       = 2.7E-04,
  WCPRIME  = 3.0E-04,
  NE       = 1.5,
  KR       = 5.0E-01,
  BF2      = 1.4E+01,
  VB       = 1.368120028E+01,
  VF       = 2.587500647E-02,
  FF       = 1.027800526E-14,
  VCE      = 5.0,
  IBB      = 1.380000345E-03,
  PC       = 3.25E-03,
  $END
```

Figure A-2 PAREV Output — EQSOLVE Input TAPE2

TABLE A-1 INPUT PARAMETER LIST — SEGMENT 1 OF 3

| No. | Program Name | Symbol | Description | TAPE 5 Default | Units |
|---|---|---|---|---|---|
| 1 | RHOB | $\rho_B$ | Extrinsic Base Resistivity | .009 | ohms |
| 2 | TE | $t_E$ | Emitter Depth | $1 \times 10^{-4}$ | cm |
| 3 | AB | $A_B$ | Base Area | $5 \times 10^{-7}$ | $cm^2$ |
| 4 | RBO | $R_{BO}$ | Extrinsic Base Resistance | 0. | ohms |
| 5 | L | L | Emitter Width | $6 \times 10^{-5}$ | cm |
| 6 | H | h | Emitter Length | $6 \times 10^{-5}$ | cm |
| 7 | W | W | Base Width | $6 \times 10^{-5}$ | cm |
| 8 | RBB | $R_{BB}$ | Intrinsic Base Resistance | 0. | ohms |
| 9 | RE | $R_E$ | Extrinsic Emitter Resistance | 0.5 | ohms |
| 10 | RHOC | $\rho_C$ | Collector Resistivity | .00325 | ohm-cm |
| 11 | WCPRIME | $W_C'$ | Distance from Collector-Base Junction to Buried Layer | $3 \times 10^{-4}$ | cm |
| 12 | XO | $X_O$ | $X_O/W_C'$ is a parametric ratio | $2.7 \times 10^{-4}$ | cm |
| 13 | AE | $A_E$ | Area of Emitter | $9.8 \times 10^{-7}$ | $cm^2$ |
| 14 | RCC | $R_{CC}$ | Low Injection Extrinsic Collector Response | 7.0 | ohms |

TABLE A-1 INPUT PARAMETER LIST — SEGMENT 2 OF 3

| No. | Program Name | Symbol | Description | TAPE 5 Default | Units |
|---|---|---|---|---|---|
| 15 | T | $T$ | Junction Temperature | 27. | °C |
| 16 | VTS | $V_{TS}$ | Substrate Junction Voltage Parameter | .03 | volts |
| 17 | ISR | $I_{SR}$ | Substrate Saturation Current | $3 \times 10^{-12}$ | amps |
| 18 | CSO | $C_{SO}$ | Substrate Zero Bias Capacitance | $2 \times 10^{-12}$ | farads |
| 19 | PHISS | $\phi_{SS}$ | Substrate Built-In Junction Voltage | 0.9 | volts |
| 20 | CEO | $C_{EO}$ | Emitter Junction Zero-Bias Capacitance | $9 \times 10^{-13}$ | farads |
| 21 | PHIEO | $\phi_{EO}$ | Emitter Junction Built-In Junction Voltage | .9 | volts |
| 22 | CCO | $C_{CO}$ | Collector Junction Zero-Bias Capacitance | $8 \times 10^{-13}$ | farads |
| 23 | PHICO | $\phi_{CO}$ | Collector Junction Built-In Junction Voltage | 1.2 | volts |
| 24 | IER | $I_{ER}$ | Nonideal Emitter Diode Saturation Current | $3.2 \times 10^{-14}$ | amps |
| 25 | NE | $\eta_E$ | Nonideal Emitter Exponent Multiplier | 1.5 | ---- |

TABLE A-1 INPUT PARAMETER LIST — SEGMENT 3 OF 3

| No. | Program Name | Symbol | Description | TAPE 5 Default | Units |
|---|---|---|---|---|---|
| 26 | IS | $I_S$ | Forward Saturation Current | $3.2 \times 10^{-16}$ | amps |
| 27 | BETAO | $\beta_o$ | Maximum Forward Current Ratio | 55 | ---- |
| 28 | IBR | $I_{BR}$ | Nonideal Collector Diode Saturation Current | $3. \times 10^{-13}$ | amps |
| 29 | NC | $\eta_C$ | Nonideal Collector Diode Saturation Current | 1.8 | amps |
| 30 | BETAR | $\beta_r$ | Reverse Maximum Current Ratio | 1.5 | ---- |
| 31 | VER | $V_{ER}$ | Forward Early Voltage | 20. | volts |
| 32 | VCR | $V_{CR}$ | Inverse Early Voltage | 60. | volts |
| 33 | QFN | $Q_{FN}$ | Normalized Forward Injection Coefficient | $1.5 \times 10^{-16}$ | ---- |
| 34 | QRN | $Q_{RN}$ | Normalized Reverse Injection Coefficient | $1.5 \times 10^{-12}$ | ---- |
| 35 | TAUFO | $\tau_{FO}$ | Forward Base Transit Time | $1.59 \times 10^{-9}$ | sec |
| 36 | TAUR | $\tau_R$ | Reverse Base Transit Time | $1.27 \times 10^{-9}$ | sec |
| 37 | KR | $K_R$ | AC Crowding Parameter | 0.6 | ---- |
| 38 | VT | VT | Junction Diode Exponent Coefficient | 0.0259 | volts |
| 39 | VB | $V_B$ | Mathematical Fitting Parameters for Base Pushout Simulation | 17.79 | volts |
| 40 | BF2 | $B_{F2}$ | | 13.64 | ---- |
| 41 | FF | $F_F$ | | $1.336 \times 10^{-14}$ | ---- |

```
17
.1E-6
.2E-6
.4E-6
.7E-6
1.0E-6
2.0E-6
4.0E-6
7.0E-6
10.E-6
20.E-6
40.E-6
70.E-6
.1E-3
.2E-3
.4E-3
.7E-3
1.E-3
```

Figure A-3 TAPE4 - Base Current Input File Example

### A.2.3 Tabular Output

Local file TAPE7 is written at every $I_B$ point with the variables $V_C$, $I_B$, $I_C$, $h_{FE}$, $B_F$, $f_T$, and $V_{BE}$. TAPE7 may be listed at the termination of an interactive session to supplement the Calcomp printer plots. An example TAPE7 partial listing is shown in Figure A-4.

### A.2.4 Calcomp Output

Examples of Calcomp output graphs are shown in the sensitivity curve sets of Appendix B.

### A.2.5 User Interaction - Sample Session

The interactive session using EQSOLVE requires user input in response to terminal prompters for specification of Calcomp output details. The first request identifies the independent (x-axis), dependent (y-axis), and parametric variables by name and index number. Index number is the relative position of the variables within a COMMON block called PRAMTRS, and is used for internal program identification only. Parameter name is used for axis labeling and may be specified by alphanumeric string less than eight characters without altering graphical output. Index values are tabulated, including default values, in Figure A-5.

```
[ LIST,TAPE7

     VCPRIME = -4.572E+00      IB =  1.000E-07      IC =  1.276E-06
     HFE =  1.276E+01      BF =  1.000E+00      FT =  4.639E+06
     VBE =  5.713E-01

     VCPRIME = -4.554E+00      IB =  2.000E-07      IC =  3.212E-06
     HFE =  1.606E+01      BF =  1.001E+00      FT =  1.143E+07
     VBE =  5.953E-01

     VCPRIME = -4.536E+00      IB =  4.000E-07      IC =  7.890E-06
     HFE =  1.973E+01      BF =  1.003E+00      FT =  2.719E+07
     VBE =  6.186E-01

     VCPRIME = -4.522E+00      IB =  7.000E-07      IC =  1.600E-05
     HFE =  2.286E+01      BF =  1.006E+00      FT =  5.298E+07
     VBE =  6.370E-01

     VCPRIME = -4.514E+00      IB =  1.000E-06      IC =  2.491E-05
     HFE =  2.491E+01      BF =  1.009E+00      FT =  7.939E+07
     VBE =  6.485E-01
```

**Figure A-4 TAPE7 Partial Output List**

| Index | Parameter | Default | Index | Parameter | Default |
|---|---|---|---|---|---|
| 1 | RBO | 9. | 35 | NDC | 1.E16 |
| 2 | RBB | 150 | 36 | PHIC | .7 |
| 3 | RE | .5 | 37 | DNC | 48. |
| 4 | RCO | 5. | 38 | XO | 1.2E-4 |
| 5 | PC | .00325 | 39 | KR | .4 |
| 6 | BS | .33333 | 40 | TD | 20.E-12 |
| 7 | BC | .33333 | 41 | M | 2.0 |
| 8 | BE | .5 | 42 | NE | 1.5 |
| 9 | CSO | 2E-12 | 43 | IB | |
| 10 | CEO | .9E-12 | 44 | VCPRIME | |
| 11 | CCO | .8E-12 | 45 | IBB | |
| 12 | PHISS | .9 | 46 | QF | |
| 13 | PHICO | .9 | 47 | QR | |
| 14 | PHIEO | 1.2 | 48 | LAMBDAE | |
| 15 | ISR | 3.E-12 | 49 | ISS | |
| 16 | IS | 3.2E-16 | 50 | IN | |
| 17 | IER | 3.2E-14 | 51 | II | |
| 18 | IBR | 3E-13 | 52 | IO | |
| 19 | VER | 20. | 53 | ILIM | |
| 20 | VCR | 60. | 54 | BF | |
| 21 | NC | 1.8 | 55 | QBN | |
| 22 | VT | .0259 | 56 | VBE | |
| 23 | VTS | .03 | 57 | IC | |
| 24 | QFN | 1.5E-16 | 58 | HFE | |
| 25 | QRN | 1.5E-12 | 59 | FT | |
| 26 | TAUFO | 159.E-12 | 60 | VCE | 5.0 |
| 27 | TAUR | 1270E-12 | 61 | BETAE | |
| 28 | BETAO | 55. | 62 | BF2 | 13.64 |
| 29 | BETAR | 1.5 | 63 | VB | 17.793 |
| 30 | W | .6E-4 | 64 | VF | 2.59E-3 |
| 31 | AE | 9.8E-7 | 65 | FF | 1.336E-14 |
| 32 | VLIM | 6.E6 | 66 | F | |
| 33 | DNB | 22.6 | 67 | BFO | |
| 34 | WCPRIME | 3.E-4 | | | |

Figure A-5 Common Parameter Indices

A typical prompter-response dialogue is as follows:

```
ENTER,IDNME,INDEX,DPNME,INDEX,PARNME,INDEX
?|*VBE*,56,*IC*,57,*RBO*,1 |← user supplied
```

The dialogue requested an IC versus VBE plot with resistor RBO as the varying parameter.

The next dialogue requests Calcomp type, number of curves per plot, and the varying parameter values. Curve type is specified by the following index list:

| X-Axis | Y-Axis | Index |
|---|---|---|
| LINEAR | LINEAR | 1 |
| LINEAR | LOG | 2 |
| LOG | LINEAR | 3 |
| LOG | LOG | 4 |

A prompter-response dialogue requesting a linear (x) - log (Y) plot with three values of a varying parameter equal to 90, 9, and .9 (RBO values) is: (NCURVES ≤ 5)

```
ENTER,TYPE,NCURVES,PARAM VALUES
?|2,3,90.,9.,.9|← user supplied
```

The third and final dialogue requests adjustments in size of the x-axis and y-axis, and number of points between sumbols on a curve. A sample dialogue requesting a 6 inch x-axis, 7 inch y-axis, and plot symbols every 3 points (default values) is:

```
UPDATE XINCH,YINCH,MARKS(5) IF REQD
$CURV
|YINCH=7,XINCH=6,MARKS=3,3,3$|← user supplied
```

Note that three entries of three (3) are required since three curves are requested by NCURVES prompter.

An actual teletype session for Calcomp output using the above dialogues is given in Figure A-6. The default x-axis, y-axis size and symbol density are used by supplying a terminating dollar sign ($). An actual Calcomp output for this session is given in Figure A-7.

```
 07/13/77. 10.37.10.
 TRW/TSS C174 - 07/11/77.

USER NUMBER:
JOB NAME  PLRG.
PORT      220.
[ GET,TAPE4,EQSOLVE,TAPE5=EQDATA1
[ RX,I=EQSOLVE
[ LGO
 ENTER INDNME,INDEX,DPNME,INDEX,PARNME,INDEX
? *VBE*,56,*IC*,57,*RBO*,1
 ENTER TYPE,NCURVES,PARAM VALUES
? 2,3,90,.9,9
 UPDATE YINCH,XINCH,MARKS(5) IF REQD
  $CURV
? $
 TYPE 1 FOR ANOTHER CASE
? 1
 ENTER INDNME,INDEX,DPNME,INDEX,PARNME,INDEX
 <etc.>
```

Figure A-6  Interactive Session Printout

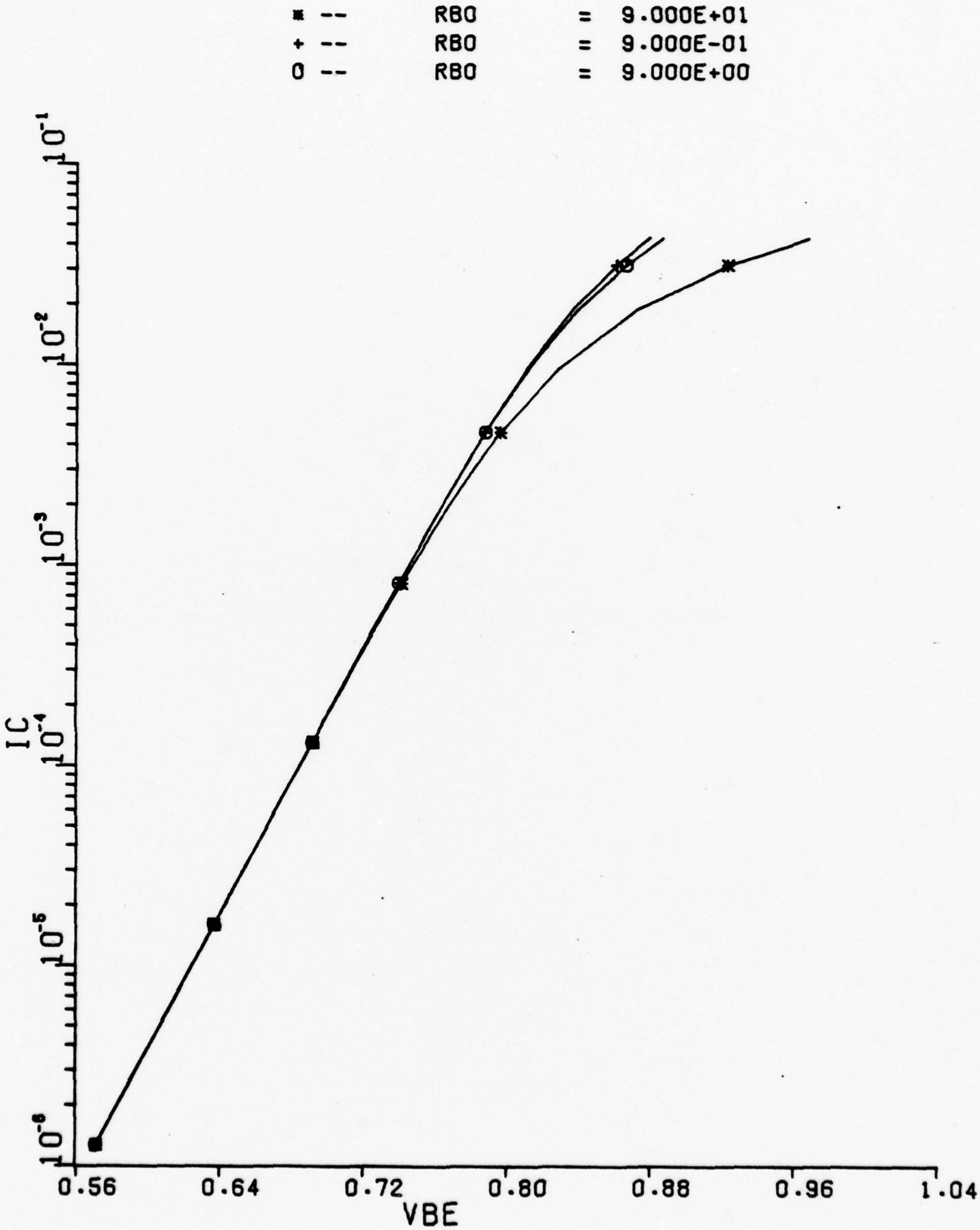



Figure A-7 Sample Session Calcomp Output

## A.3 Program Calculations

The EQSOLVE program performs calculations of internal and external parameters of a given modeled transistor at a set of base current values and at a fixed VCE in the normal (forward) regime. Due to the dependencies of the model equations, a nonlinear root finder routine is required to calculate internal currents and voltages, and an iteration path is used to converge the internal currents and junction voltages to values which satisfy both the model equations and the external constraints of a fixed base current IB and collector-emitter voltage VCE. An overview of the program flow is shown in Figure A-8, illustrating the internal variables Z, $V_E'$ and $I_C$ generated by three separate calls to a root finder routine called GRTM. An auxiliary subroutine is used in each call, which describes the controlling equation containing the variable to be found. Details of the GRTM and auxiliary subroutines are explained in other sections of this document.

The set of calculations begins with a requested current point, $I_B$, and model parameters (user supplied or default). An initial guess of collector junction intrinsic voltage is given as

$$V_C' = -V_{CE} \tag{A-1}$$

and GRTM is called to evaluate Z from the equation

$$Z\mathrm{Tan}(Z) = I_B/I_{BB} \tag{A-2}$$

Given Z,

$$R_B = \frac{R_{BB}[\mathrm{Tan}(Z) - Z]}{4 \cdot Z \cdot \mathrm{Tan}(Z)} \tag{A-3}$$

and

$$A_{EF} = A_E \cdot \mathrm{Sin}(2Z)/2Z \tag{A-4}$$

The estimate $V_C'$ is now required to compute $V_E'$ from

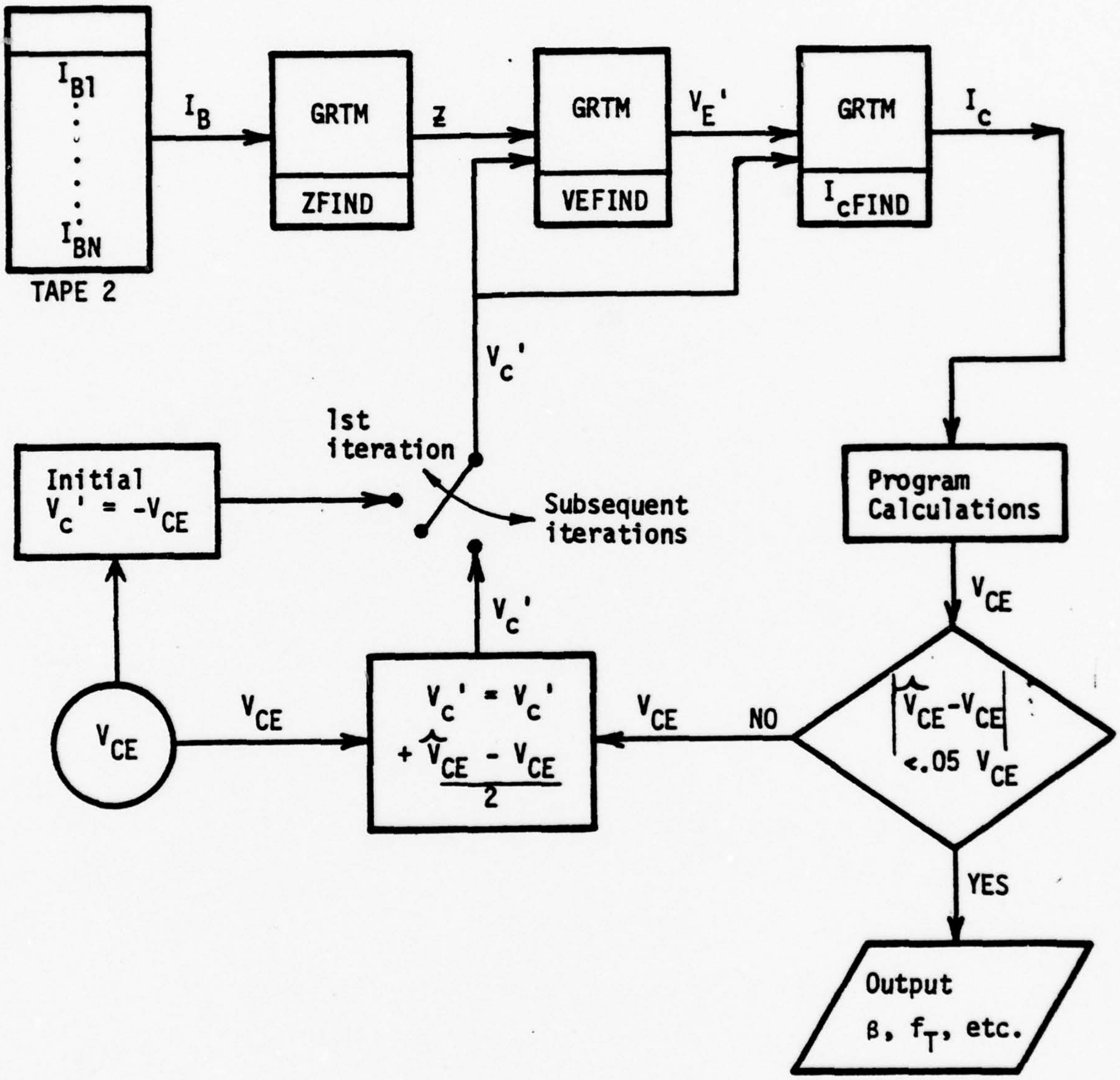



Figure A-8 EQSOLVE Program Flow Diagram

$$I_B = I_{ER}[\exp(V_E'/N_E V_T) - 1] + \frac{I_S}{\beta_o}[\exp(V_E'/V_T) - 1]$$

$$+ \frac{I_S}{\beta_r}[\exp(V_C'/V_T) - 1] + I_{BR}[\exp(V_C'/N_C V_T) - 1] \qquad \text{(A-5)}$$

by another call to the root finder routine. The intrinsic junction voltages are now known, and the current and charge terms are calculated. Prior to this, if $R_{CC}$ is not given as input, the calculation

$$R_{CC} = \frac{\rho_C W_C'}{A_{EF}} \qquad \text{(A-6)}$$

is performed. Then,

$$I_N = I_S[\exp(V_E'/V_T) - 1] \qquad \text{(A-7)}$$

$$I_I = I_S[\exp(V_C'/V_T) - 1] \qquad \text{(A-8)}$$

$$Q_F = Q_{FN}[\exp(V_E'/V_T) - 1] \qquad \text{(A-9)}$$

$$Q_R = Q_{RN}[\exp(V_C'/V_T) - 1] \qquad \text{(A-10)}$$

$$I_{SS} = I_{SR}[\exp(V_C'/V_{TS}) - 1] \; . \qquad \text{(A-11)}$$

The next block of calculations is Early effect and base pushout parameters.

$$\lambda_E = 1 + V_E'/V_{ER} + V_C'/V_{CR} \; , \qquad \text{(A-12)}$$

$$F = FF[\exp(V_E'/V_F) - 1] \; , \qquad \text{(A-13)}$$

$$B_{FO} = 1 + B_{F2}[\exp(V_C'/V_B)] \; , \qquad \text{(A-14)}$$

$$B_F = B_{FO} + (1 - B_{FO})[(\exp(-F)] \; . \qquad \text{(A-15)}$$

The third call to the root finder routine is made to evaluate $I_C$ from the equations

$$Q_{BN} = \frac{\lambda_E}{2} + \left[\left(\frac{\lambda_E}{2}\right)^2 + B_F Q_F + Q_R\right]^{1/2} \tag{A-16}$$

$$I_C = I_{SS} - I_{BR}\left[\exp(V_C'/N_C V_T) - 1\right] - \frac{I_S}{\beta_r}\left[\exp(V_C'/V_T) - 1\right] + \frac{I_N - I_I}{Q_{BN}} \tag{A-17}$$

Additionally, the program evaluates

$$\lambda_{CC} = \frac{X_o}{W_C'}\left(\frac{B_F - 1}{B_{F2}}\right)^{1/2} \tag{A-18}$$

$$R_C = R_{CC}(1 - \lambda_{CC}) \tag{A-19}$$

$$I_{BE} = \frac{I_S}{\beta_o}\left[\exp(V_E'/V_T) - 1\right] \tag{A-20}$$

$$I_{BC} = \frac{I_S}{\beta_r}\left[\exp(V_C'/V_T) - 1\right] \tag{A-21}$$

$$V_{BE} = I_B \cdot R_{BO} + (I_{BE} + I_{BC}) \cdot R_B + V_E' + (I_B + I_C) \cdot R_E \tag{A-22}$$

Finally,

$$\hat{V}_{CE} = V_X = I_C \cdot R_{CO} + (I_C - I_{SS}) \cdot R_C - V_C' + V_E' + (I_B + I_C) \cdot R_E \tag{A-23}$$

The comparison of $\hat{V}_{CE}$ to $V_{CE}$ is now performed.

If $|\hat{V}_{CE} - V_{CE}| \leq .05\, V_{CE}$, the calculations proceed. Otherwise, a new estimate of $V_C'$ is generated by

$$\hat{V}_C' = V_C' + (\hat{V}_{CE} - V_{CE})/2 \tag{A-24}$$

and program contr... s transferred to the second call to GRTM following equation (A-5).

Once a "suitably close" value for $\hat{V}_{CE}$ is found, the program calculates several parameters of interest at the operating point ($I_B$, $V_{CE}$). The first quantities are the base pushout and forward base charge sensitivities,

$$S_{BE} = \frac{(B_{FO} - 1)\cdot FF\cdot \exp(V_E'/V_F - F)}{B_F * V_F} \tag{A-25}$$

$$S_{BC} = \frac{B_{F2}\cdot \exp(V_C'/V_B)\cdot[1 - \exp(-F)]}{B_F\cdot V_B} \tag{A-26}$$

$$S_{QE} = \frac{[I_C\cdot B_F\cdot Q_{FN}/(I_S\cdot V_T)](1 + V_T\cdot S_{BE})}{2\cdot Q_{BN} - \lambda_E} \tag{A-27}$$

$$S_{QC} = \left(\frac{1}{2\cdot V_{CR}\cdot Q_{BN}} + \frac{1}{2\cdot V_{CR}/(2\cdot Q_{BN} - \lambda_E)}\right)\left(\frac{\lambda_E}{Q_{BN}} + 2\cdot V_{CR}\cdot B_F\cdot Q_{FN}\cdot I_C\cdot S_{BC}/I_S\right) \tag{A-28}$$

The forward and reverse incremental transconductances are given by

$$gmf = (I_C/V_T)\cdot(1 - S_{QE}/V_T) \tag{A-29}$$

$$gmr = I_C\cdot S_{QC} \tag{A-30}$$

The program now checks if base pushout is in evidence ($B_F > 1$) and calculates

$$R_{OC} = \begin{cases} R_{CC} & B_F = 1 \\ R_C - \dfrac{I_C\cdot R_{CC}\cdot(X_O/W_C')\cdot\left(\dfrac{B_F\cdot S_{BE}}{gmf} - \dfrac{B_F\cdot S_{BC}}{gmr}\right)}{2\cdot B_{F2}\cdot[(B_F - 1)/B_{F2}]^{1/2}} & B_F > 1 \end{cases} \tag{A-31}$$

and

$$R_{OB} = 2\cdot_{VT}/(3\cdot I_{BB}) \tag{A-32}$$

The junction capacitances are assigned values by the equations

$$C_{jE} = \begin{cases} \dfrac{C_{EO}}{(1 - V_E'/\phi_{EO})^{B_E}} & V_E' < \phi_{EO} \\ C_{EO}\cdot(1 + \dfrac{B_E \cdot V_E'}{\phi_{EO}}) & V_E' > \phi_{EO} \end{cases} \tag{A-33}$$

$$C_{jC} = \begin{cases} \dfrac{C_{CO}}{(1 - V_C'/\phi_{CO})^{B_C}} & V_C' < 0 \\ C_{CO}\cdot(1 + \dfrac{B_C \cdot V_C'}{\phi_{CO}}) & V_C' > 0 \end{cases} \tag{A-34}$$

Diffusion capacitances are

$$C_{DE} = B_F \cdot \tau_{FO} \cdot (gmf + I_C \cdot S_{BE}) \tag{A-35}$$

$$C_{DC} = B_F \cdot \tau_{FO} \cdot (I_C \cdot S_{BC} - gmr) \tag{A-36}$$

yielding total capacitances given by

$$C_{TE} = C_{DE} + C_{jE} \tag{A-37}$$

$$C_{TC} = C_{DC} + C_{jC} \tag{A-38}$$

Substrate voltage is assumed equal to collector junction voltage, and

$$C_{SS} = \begin{cases} \dfrac{C_{SO}}{(1 - V_C'/\phi_{SS})^{B_S}} & V_C' < 0 \\ C_{SO}\cdot(1 + B_S\cdot V_C'/\phi_{SS}) & V_C' > 0 \end{cases} \qquad \text{(A-39)}$$

The time moment calculations proceed with

$$g_{BE} = \frac{I_{BE}}{V_T} + \frac{I_{ER}}{n_E\cdot V_T}\cdot[\exp(V_E'/n_E\cdot V_T) - 1] \qquad \text{(A-40)}$$

$$F_E = 1 + (gmf + g_{BE})\cdot R_E \qquad \text{(A-41)}$$

$$g_B = g_{BE}/F_E \qquad \text{(A-42)}$$

$$C_E = C_{TE}/F_E \qquad \text{(A-43)}$$

$$go = gmr/F_E \qquad \text{(A-44)}$$

$$gm = (gmf - gmr)/F_E \qquad \text{(A-45)}$$

$$R_L' = \frac{R_{OC} + R_{CO}}{1 + go\cdot(R_{OC} + R_{CO})} \qquad \text{(A-46)}$$

$$r_{11} = 1/g_B \qquad \text{(A-47)}$$

$$r_{22} = R_L' + (1 + gm\cdot R_L')\cdot r_{11} \qquad \text{(A-48)}$$

$$r_{33} = R_{OB} + r_{11} + (1 + gm\cdot r_{11})\cdot R_L' \qquad \text{(A-49)}$$

$$r_{44} = \frac{(1 + go\cdot R_{OC})\cdot R_{CO}}{1 + go\cdot(R_{OC} + R_{CO})} \qquad \text{(A-50)}$$

and

$$T_1 = r_{11}\cdot C_{TE} + K_R\cdot r_{22}\cdot C_{TC}\cdot(1 - K_R)\cdot r_{33}\cdot C_{TC} + r_{44}\cdot C_{SS}. \qquad \text{(A-51)}$$

The final parameters of interest are calculated as

$$\beta_F = \left(\frac{gm}{g_B}\right)[1 + go(R_{OC} + R_{CO})] \tag{A-52}$$

$$f_T = \frac{\beta_F}{2 \cdot \pi \cdot T_1} \tag{A-53}$$

$$h_{FE} = I_C/I_B \tag{A-54}$$

After output of $I_B$, $I_C$, $h_{FE}$, $B_F$, $f_T$, $V_{BE}$, and any other user-requested values, the program control is returned to the beginning of the calculations, and the calculations are performed again with a new value of $I_B$.

A.4 Detailed Subroutine Structure - GRTM

A.4.1 Module Usage and Interface

GRTM is a general root finder routine which is called three times during a pass through the EQSOLVE equations. It is called to determine the onset parameter Z, $V_E'$, and $I_C$. Linkage into GRTM is accomplished by providing auxiliary subroutines which contain an equation that evaluates to zero for the proper value of the variable to be found. The auxiliary subroutine names and equations used in EQSOLVE calls are as follows:

| Name | Equation |
|---|---|
| ZFIND | (A-2) |
| VEFIND | (A-5) |
| ICFIND | (A-17) |

A.4.2 Subroutine Input

Input to GRTM is the auxiliary function name, an initial guess of roots requested, and an iteration convergence value described in section 4.1.4.4. The maximum iteration value is set at 50 and a convergence criteria of $1 \times 10^{-6}$ is used for EQSOLVE.

A.4.3 Subroutine Output

The onset parameter Z, intrinsic base-emitter voltage $V_{E'}$, and collector current $I_C$, are outputs of GRTM when called from EQSOLVE.

A.4.4 Subroutine Calculations

GRTM uses Muller's method to find the roots of f(x). This method is detailed in Section 4.3.2.

## A.5 EQSOLVE CODE LISTING

```
      PROGRAM EQSOLVE(INPUT,OUTPUT,TAPE4,TAPE2,TAPE6,TAPE7,TAPE50,
     * TAPE3=INPUT)
C     PROGRAM WILL SOLVE A SERIES OF EQUATIONS TO DETERMINE THE EFFECTS
C     OF PROCESS PARAMETER VARIATION ON SEMICONDUCTOR DEVICES.
      COMMON /DATA/ FX(500,5), X(500,5), CGVAR(5), CGLBL, DPEND,
     * INDPEND, TYPE, NPTS, NCURVES, YINCH, XINCH, MARKS(5)
      COMMON /PRAMTRS/ RBO, RBB, RE, RCO, PC, BS, BC, BE, CSO, CEO,
     * CCO, PHISS, PHICO, PHIEO, ISR, IS, IER, IBR, VER, VCR, NC, VT,
     * VTS, QFN, QRN, TAUFO, TAUR, BETAO, BETAR, W, AE, VLIM, DNB,
     * WCPRIME, NDC, PHIC, DNC, XO, KR, TD, M, NE, IB, VCPRIME, IBB,
     * QF, QR, LMBDAE, ISS, IN, II, IO, ILIM, BF, QBN, VBE, IC, HFE,
     * FT, VCE, BETAF, BF2, VB, VF, FF, F, BFQ
      DIMENSION LINK(67)
      NAMELIST /CURV/ YINCH, XINCH, MARKS
      REAL IBB, IB, ISR, IS, IER, IBR, KR, M, NC, NE, IO, ILIM, NDC,
     * IN, II, ISS, IBE, IBC, K1, K2, LMBDAE, IC, LMBDACC, LASTZ,
     * LASTVE, LINK
      EQUIVALENCE (RBO,LINK(1))
      NAMELIST /TRANS/ RBO, RBB, RE, RCO, BS, BC, BE, CSO, CEO,
     * CCO, PHISS, PHICO, PHIEO, ISR, IS, IER, IBR, VER, VCR, NC, VT,
     * VTS, QFN, QRN, TAUFO, TAUR, BETAO, BETAR, AE,
     * WCPRIME, XO, NE, KR, BF2,VB,VF,FF,VCE,IBB
    1 FORMAT(///,5X,*VCPRIME = *,E10.3,5X,*IB = *,E10.3,5X,*IC = *,
     * E10.3,/,5X,*HFE = *,E10.3,5X,*BF = *,E10.3,5X,*FT = *,
     * E10.3,5X,/,5X,*VBE = *,E10.3)
      INTEGER TYPE, YPTR, XPTR, CGPNTR, GRAPHS
      EXTERNAL ZFIND, VEFIND, ICFIND
      CALL NMLEOF
      REWIND 50
      CALL LOOK(50)
      CALL PLOT(0.,1.,23)
   16 REWIND 2
    4 READ(2,TRANS)
      IF(EOF,2) 5,4
    5 XINCH=6. $ YINCH=7. $ MARKS(1)=MARKS(2)=MARKS(3)=3
              DISPLAY *ENTER INDNME,INDEX,DPNME,INDEX,PARNME,INDEX*
              ACCEPT INDPEND,XPTR,DPEND,YPTR,CGLBL,CGPNTR
              DISPLAY *ENTER TYPE,NCURVES,PARAM VALUES*
              ACCEPT TYPE,NCURVES,(CGVAR(I),I=1,NCURVES)
              DISPLAY *UPDATE YINCH,XINCH,MARKS(5) IF REQD*
              READ(3,CURV)
      LASTZ = 1.0
```

```
      LASTVE = .755555
      Q = 1.602E-19
      EPSILON = 1.062E-12
      PI = 3.14159
      GRAPHS = 0
9     NPASS = 0
      REWIND 4
      ACCEPT(4) NPTS
      GRAPHS = GRAPHS + 1
      LINK(CGPNTR)=CGVAR(GRAPHS)
6     ACCEPT(4) IB
      IF(EOF,4) 7,8
8     VALUES = LASTZ
      VCPRIME = -VCE
      NPASS = NPASS + 1
      CALL GRTM(1,VALUES,0,50,ZFIND,0,1.E-6)
      Z = LASTZ - VALUES
      RB = (RBB * (TAN(Z) - Z)) / ((4.0 * Z) * (TAN(Z)**2))
      AEF = AE * SIN(2.0 * Z) / (2.0 * Z)
14    VALUES = LASTVE
      CALL GRTM(1,VALUES,0,50,VEFIND,0,1.E-6)
      VEPRIME = LASTVE - VALUES
      RCC = (PC * WCPRIME) / AEF
      IN = IS * (EXP(VEPRIME/VT) - 1.0)
      II = IS * (EXP(VCPRIME/VT) - 1.0)
      QF = QFN * (EXP(VEPRIME/VT) - 1.0)
      QR = QRN * (EXP(VCPRIME/VT) - 1.0)
      ISS = ISR * (EXP(VCPRIME/VTS) - 1.0)
      LMBDAE = 1.0 + VEPRIME/VER + VCPRIME/VCR
      F = FF * (EXP(VEPRIME/VF) - 1.0)
      BFO = 1.0 + BF2 * EXP(VCPRIME/VB)
      BF = BFO + (1.0 - BFO) * EXP(-F)
      VALUES = IO
      CALL GRTM(1,VALUES,0,50,ICFIND,0,1.E-6)
      IC = VALUES
      LMBDACC =(XO/WCPRIME)*((BF-1.)/BF2)**.5
      RC = RCC * (1.0 - LMBDACC)
      IBE = (IS/BETAD) * (EXP(VEPRIME/VT) - 1.0)
      IBC = (IS/BETAR) * (EXP(VCPRIME/VT) - 1.0)
      VBE = IB * RBO + (IBE + IBC) * RB + VEPRIME + (IB + IC) * RE
      VX = IC * RCO + (IC - ISS) * RC - VCPRIME + VEPRIME +
     * (IB + IC) * RE
```

```
      IF(ABS(VX-VCE) .LE. .05*VCE) GO TO 13
      VCPRIME = VCPRIME + ((VX-VCE)/2.0)
      GO TO 14
   13 SBE = ((BFO - 1.0) * FF * EXP(VEPRIME/VF - F)) / (BF * VF)
      SBC = (BF2 * EXP(VCPRIME/VB) * (1.0 - EXP(-F))) / (BF * VB)
      SQE = (IC * BF * QFN / (IS * VT)) * (1.0 + VT * SBE) /
     * (2.0 * QBN - LMBDAE)
      SQC = (1.0 / (2.0 * VCR * QBN)) + ((1.0 / (2.0 * VCR) /
     * (2.0 * QBN - LMBDAE)) * ((LMBDAE/QBN) + (2.0 * VCR * BF * QFN
     * + IC * SBC / IS)))
      GMF = (IC/VT) * (1.0 - (SQE * VT))
      GMR = IC * SQC
      ROC = RCC
      IF(BF.GT.1.)ROC=RC-IC*RCC*(XO/WCPRIME)*(BF*SBE/GMF-BF*SBC/GMR)/
     + (2.*BF2*((BF-1.)/BF2)**.5)
      ROB = 2.*VT/(3.*IBB)
      IF(VEPRIME .LT. PHIEO) CJE = CEO/((1.0 - VEPRIME/PHIEO)**BE)
      IF(VEPRIME .GE. PHIEO) CJE = CEO * (1.0 + BE * VEPRIME/PHIEO)
      IF(VCPRIME .LE. 0.0) CJC = CCO/((1.0 - VCPRIME/PHICO)**BC)
      IF(VCPRIME .GT. 0.0) CJC = CCO * (1.0 + BC*VCPRIME/PHICO)
      CDE = BF * TAUFO * (GMF + IC * SBE)
      CDC = BF * TAUFO * (IC * SBC - GMR)
      CTE = CDE + CJE
      CTC = CDC + CJC
      IF(VCPRIME .LE. 0.0) CSS = CSO/((1.0 - VCPRIME/PHISS)**BS)
      IF(VCPRIME .GT. 0.0) CSS = CSO * (1.0 + BS*VCPRIME/PHISS)
      GBE = IBE/VT + IER/(NE * VT) * (EXP(VEPRIME/(NE * VT)) - 1.0)
      FE = 1.0 + (GMF + GBE) * RE
      GB = GBE/FE
      CE = CTE/FE
      GO = GMR/FE
      GM = (GMF - GMR)/FE
      RLPRIME = (ROC + RCO)/((1.0 + GO * (RCC + RCO)))
      R11 = 1.0/GB
      R22 = RLPRIME + (1.0 + GM * RLPRIME) * R11
      R33 = ROB + R11 + (1.0 + GM * R11) * RLPRIME
      R44 = ((1.0 + GO * ROC) * RCO)/(1.0 + GO * (ROC + RCO))
      T1 = R11 * CTE * KR * R22 * CTC + (1.0 - KR) * R33 * CTC +
     * R44 * CSS
      BETAF = (GM/GB)/(1.0 + GO * (ROC + RCO))
      FT = BETAF/(2.0 * PI * T1)
      HFE = IC/IB
```

```
      WRITE(7,1) VCPRIME, IB, IC, HFE, BF, FT, VBE
      FX(NPASS,GRAPHS) = LINK(YPTR)
      X(NPASS,GRAPHS) = LINK(XPTR)
      IF(NPASS .LT. NPTS) GO TO 5
      IF(GRAPHS .LT. NCURVES) GO TO 9
    7 CALL PLTEXEC
      DISPLAY *TYPE 1 FOR ANOTHER CASE*
      ACCEPT III
      IF(III.EQ.1) GO TO 16
      CALL PLOT(0,0,999)
      STOP
      END
      SUBROUTINE ZFIND(Z,FZ)
C     ZFIND CALULATES Z AS A FUNCTION OF THE TANGENT OF ITSELF.
      COMMON /PRAMTRS/ SKIP1(42), IB, SKIP2, IBB, SKIP3(22)
      REAL IB, IBB
      FZ = Z * TAN(Z) - (IB / IBB)
      RETURN
      END
      SUBROUTINE VEFIND(VEPRIME,FVE)
C     VEFIND CALCULATES THE VARIABLE IB BASED ON SOME ASSUMMED VALUE OF
C     VEPRIME.
      COMMON /PRAMTRS/ SKIP1(15), IS, IER, IBR, SKIP2(2), NC, VT,
     * SKIP3(5), BETAD, BETAR, SKIP4(12), NE, IB, VCPRIME, SKIP5(23)
      REAL IER, IS, IBR, NC, NE, IB
      TERM1 = IER * (EXP(VEPRIME/(NE*VT)) - 1.0)
      TERM2 = (IS / BETAD) * (EXP(VEPRIME/VT) - 1.0)
      TERM3 = (IS / BETAR) * (EXP(VCPRIME/VT) - 1.0)
      TERM4 = IBR * (EXP(VCPRIME/(NC*VT)) - 1.0)
      FVE = TERM1 + TERM2 + TERM3 + TERM4 - IB
      RETURN
      END
      SUBROUTINE ICFIND(IC,FIC)
C     ICFIND CALCULATES THE VALUE FIC WHICH IS DEPENDENT UPON IC.  THE VALUE
C     IC AND FIC MUST BE EQUAL UPON CONVERGENCE.
      COMMON /PRAMTRS/ SKIP1(15), IS, SKIP2, IBR, SKIP3(2), NC, VT,
     * SKIP4(6), BETAR, W, SKIP5(2), DNB, WCPRIME, SKIP6(2), DNC,
     * SKIP7(6), VCPRIME, SKIP8, QF, QR, LMBDAE, ISS, IN, II, IO, ILIM,
     * BF, QBN, SKIP9(12)
      REAL IC, IO, ILIM, IS, ISS, IBR, NC, II, LMBDAE, IN
      QBN = LMBDAE/2.0 + ((LMBDAE/2.0)**2 + BF * QF + QR)**.5
      TERM1 = IBR * (EXP(VCPRIME/(NC*VT)) - 1.0)
```

```
      TERM2 = (IS/BETAR) * (EXP(VCPRIME/VT) - 1.0)
      TERM3 = (IN - II) / QBN
      FIC = ISS - TERM1 - TERM2 + TERM3 - IC
      RETURN
      END
      SUBROUTINE PLTEXEC
C     PLTEXEC SELECTS THE ROUTINES TO BE TRANSFERRED TO SETUP DEPENDING
C     UPON WHICH TYPE OF PLOT IS DESIRED.
C
C     TYPE = 1 PLOT IS LINEAR/LINEAR
C     TYPE = 2 PLOT IS LOG/LINEAR(Y/X)
C     TYPE = 3 PLOT IS LINEAR/LOG(Y/X)
C     TYPE = 4 PLOT IS LOG/LOG
C
      COMMON /DATA/ SKIP1(5008), TYPE, SKIP2(9)
      INTEGER TYPE
      EXTERNAL SCALE, AXIS, LINE, SCALG, LGAXS, LGLIN
      LOGTYPE = -2
      IF(TYPE .EQ. 1) CALL SETUP(SCALE,AXIS,SCALE,AXIS,LINE,LOGTYPE)
      LOGTYPE = 1
      IF(TYPE .EQ. 2) CALL SETUP(SCALG,LGAXS,SCALE,AXIS,LGLIN,LOGTYPE)
      LOGTYPE = -1
      IF(TYPE .EQ. 3) CALL SETUP(SCALE,AXIS,SCALG,LGAXS,LGLIN,LOGTYPE)
      LOGTYPE = 0
      IF(TYPE .EQ. 4) CALL SETUP(SCALG,LGAXS,SCALG,LGAXS,LGLIN,LOGTYPE)
      RETURN
      END
      SUBROUTINE SETUP(YSCALE,YAXIS,XSCALE,XAXIS,CURVES,LOGTYPE)
C     SETUP IS THE EXECUTIVE FOR GENENRATING THE PLOTS.
      COMMON /DATA/ FX(2500), X(2500), CGVAR(5), CGLBL, DPEND,
     * INDPEND, TYPE, NPTS, NCURVES, YINCH, XINCH, MARKS(5)
      DIMENSION TITLE(4), CHARS(5), CHRINDX(5)
      INTEGER TYPE, BASE
      DATA CHARS /4H* --,4H+ --,4HO --,4HS --,4HP --/
      DATA CHRINDX /11,3,1,5,2/
    1 FORMAT(A10,A10,*= *,E10.3)
      CALL PLOT(8.5,0.,-3)
C
C     Y AXIS PREPARATION
C
      BASE = 1
      INC = 0
```

```
      LOOPS = NCURVES
      YMINALL = 1.E200
      DELYALL = YMAXALL = -1.E200
    6 CALL YSCALE(FX(BASE),YINCH,NPTS+INC,1)
      IF(TYPE .EQ. 1 .OR. TYPE .EQ. 3) YMAX = FX(BASE+NPTS+INC) +
     * YINCH * FX(BASE+NPTS+INC+1)
      IF(TYPE .EQ. 2 .OR. TYPE .EQ. 4)
     * CALL FORMAX(FX(BASE+NPTS+INC),FX(BASE+NPTS+INC+1),YMAX,YINCH)
      IF(YMAXALL .LT. YMAX) YMAXALL = YMAX
      IF(YMINALL .GT. FX(BASE+NPTS+INC)) YMINALL = FX(BASE+NPTS+INC)
      IF(DELYALL .LT. FX(BASE+NPTS+INC+1)) DELYALL = FX(BASE+NPTS+INC+1)
      LOOPS = LOOPS - 1
      IF(LOOPS .EQ. 0) GO TO 7
      BASE = BASE + 500
      FX(BASE+NPTS) = YMINALL
      FX(BASE+NPTS+1) = YMAXALL
      INC = 2
      GO TO 6
    7 CALL YAXIS(0.0,0.0,DPEND,10,YINCH,90.,YMINALL,DELYALL)
C
C     X AXIS PREPARATION
C
      BASE = 1
      INC = 0
      LOOPS = NCURVES
      XMINALL = 1.E200
      DELXALL = XMAXALL = -1.E200
    8 CALL XSCALE(X(BASE),XINCH,NPTS+INC,1)
      IF(TYPE .EQ. 1 .OR. TYPE .EQ. 2) XMAX = X(BASE+NPTS+INC) +
     * XINCH * X(BASE+NPTS+INC+1)
      IF(TYPE .EQ. 3 .OR. TYPE .EQ. 4)
     * CALL FORMAX(X(BASE+NPTS+INC),X(BASE+NPTS+INC+1),XMAX,XINCH)
      IF(XMAXALL .LT. XMAX) XMAXALL = XMAX
      IF(XMINALL .GT. X(BASE+NPTS+INC)) XMINALL = X(BASE+NPTS+INC)
      IF(DELXALL .LT. X(BASE+NPTS+INC+1)) DELXALL = X(BASE+NPTS+INC+1)
      LOOPS = LOOPS - 1
      IF(LOOPS .EQ. 0) GO TO 9
      BASE = BASE + 500
      X(BASE+NPTS) = XMINALL
      X(BASE+NPTS+1) = XMAXALL
      INC = 2
      GO TO 8
```

```
    9 CALL XAXIS(0.0,0.0,INDPEND,-1C,XINCH,C.C,XMINALL,DELXALL)
C
C     GENERATE CURVES AND PLOT LEGEND
C
      BASE = LOOPS = 1
      IF(LOGTYPE .GT. -2) GO TO 3
C
C     LINEAR/LINEAR PLOT
C
   13 FX(BASE+NPTS) = YMINALL
      FX(BASE+NPTS+1) = DELYALL
      X(BASE+NPTS) = XMINALL
      X(BASE+NPTS+1) = DELXALL
      CALL CURVES(X(BASE),FX(BASE),NPTS,1,MARKS(LOOPS),CHRINDX(LOOPS))
      IF(LOOPS .EQ. NCURVES) GO TO 4
      LOOPS = LOOPS + 1
      BASE = BASE + 500
      GO TO 13
C
C     ONE OR BOTH AXES ARE LOG
C
    3 FX(BASE+NPTS) = YMINALL
      FX(BASE+NPTS+1) = DELYALL
      X(BASE+NPTS) = XMINALL
      X(BASE+NPTS+1) = DELXALL
      CALL CURVES(X(BASE),FX(BASE),NPTS,1,MARKS(LOOPS),CHRINDX(LOOPS),
     + LOGTYPE)
      IF(LOOPS .EQ. NCURVES) GO TO 4
      LOOPS = LOOPS + 1
      BASE = BASE + 500
      GO TO 3
C
C     ANOTATE LEGEND
C
    4 LOOPS = NCURVES
      YCORD = YINCH + .6
   14 ENCODE(40,1,TITLE) CHARS(LOOPS), CGLBL, CGVAR(LOOPS)
      CALL SYMBOL(1.5,YCORD,.1,TITLE,0.0,40)
      LOOPS = LOOPS - 1
      IF(LOOPS .EQ. 0) RETURN
      YCORD = YCORD + .2
      GO TO 14
```

```
      END
      SUBROUTINE FORMAX(MINVAL,DELTA,MAXVAL,AXLNGTH)
C     FORMAX DETERMINES THE MAX VALUE OF THE INFORMATION JUST SUBMITTED
C     TO THE SCALING ROUTINE.
      REAL MINVAL, MAXVAL, LGMIN
      LGMIN = ALOG10(MINVAL)
      MAXVAL = 1.0 + 10.0**(AXLNGTH * DELTA + LGMIN)
      RETURN
      END
```

# APPENDIX B

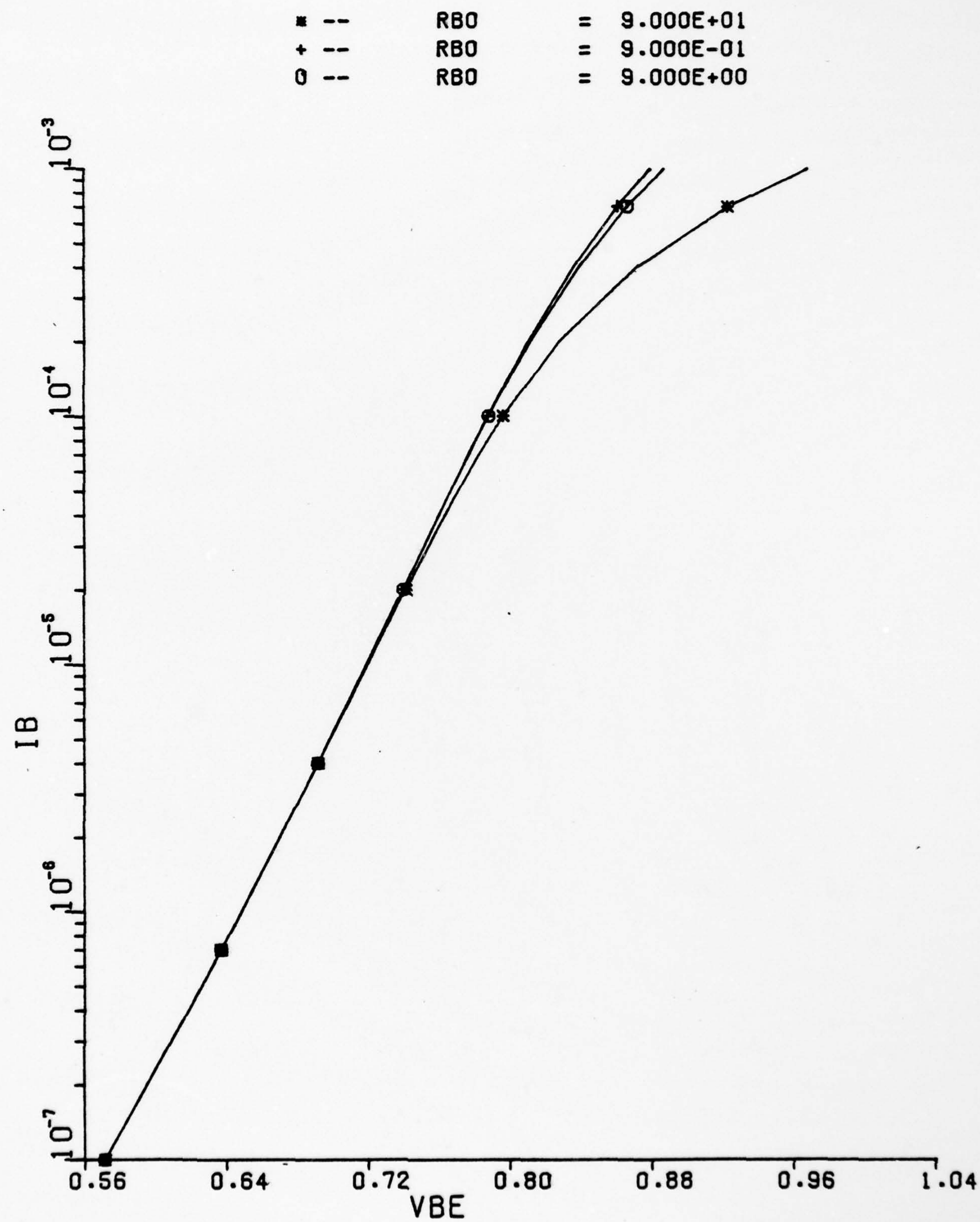
## SENSITIVITY CURVE SETS

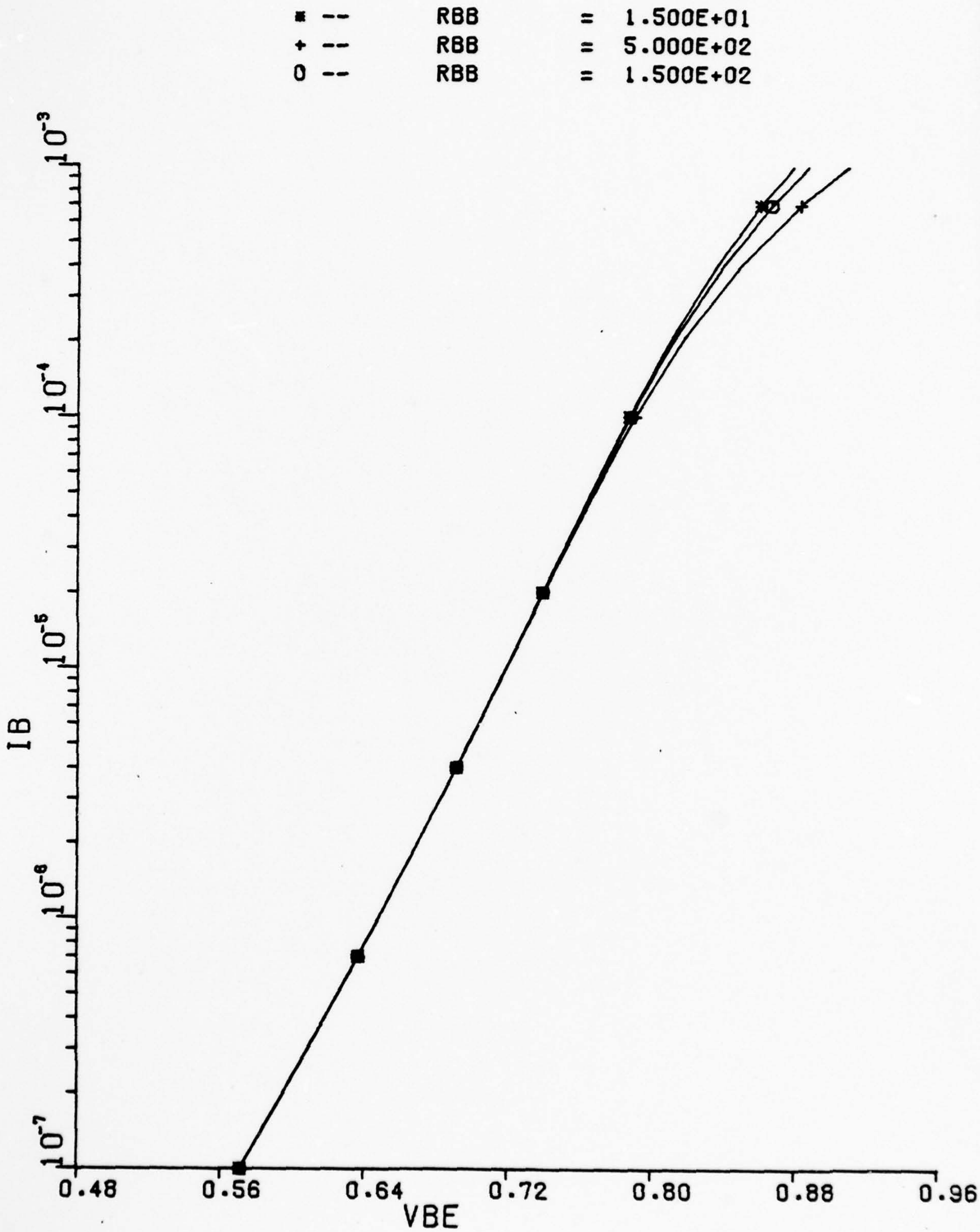
## B.0 INTRODUCTION

The sets of parametric curves comprising this appendix are Calcomp output from the EQSOLVE software code documented in Appendix A. The curve sets show the change in functional relationship of two-parameters of the Choma LSBJT model of a 2 GHz transistor under perturbation in value of a third parameter. The five sets of curves are selected, with the exception of the $B_F$ vs. $I_c$ set, as useful design-type curves which provide the essential device performance characteristics at a glance. Hence, the effects of the "third" parameter variation on these characteristic curves are produced by varying the third parameter above and below the nominal value. The $B_F$ vs. $I_c$ curves are included to provide insight into the effects of base pushout parameter values on the complex mathematical model of base pushout, an effect which is vital to understand for precise, large signal, high injection modeling.

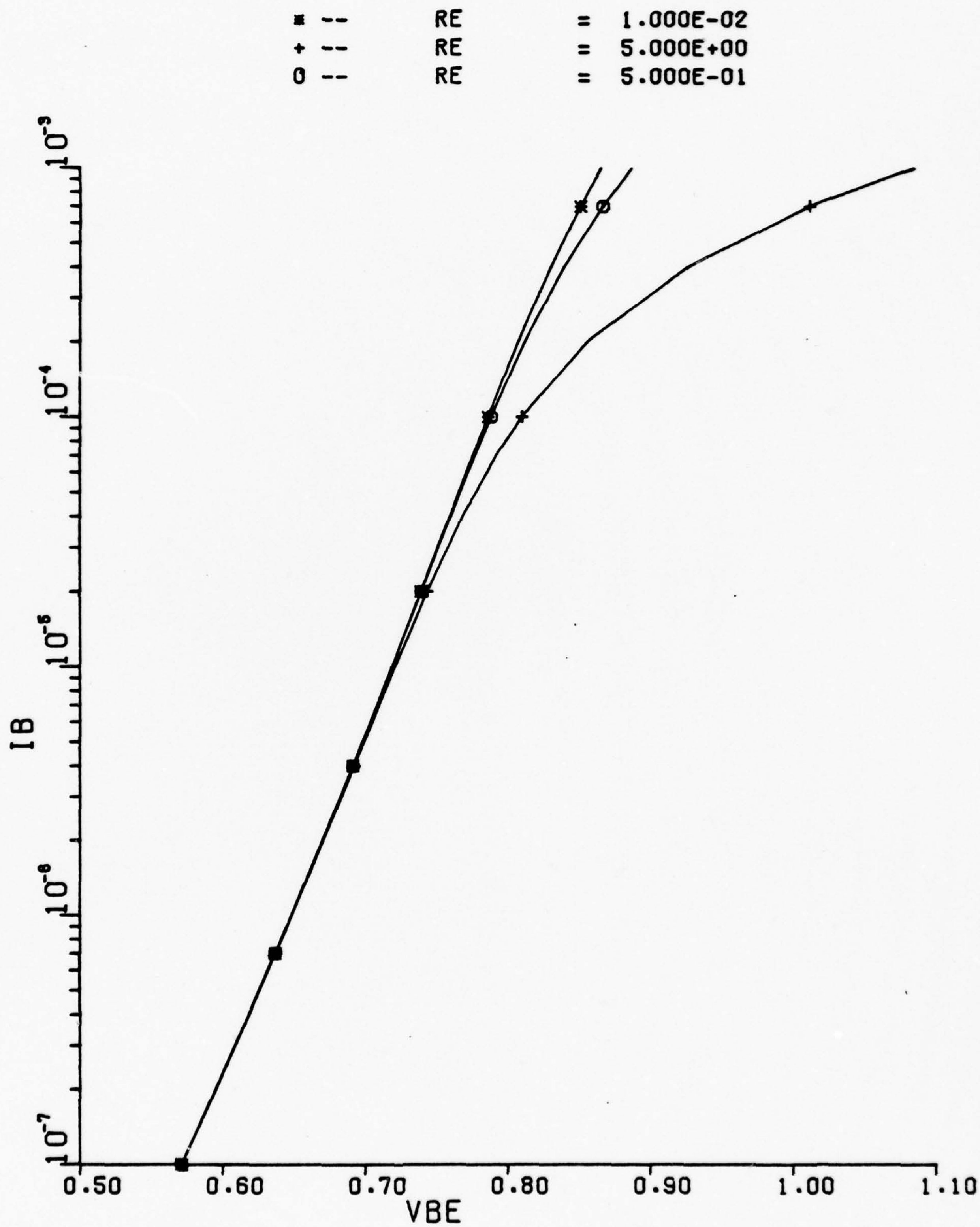
The design curves are included as a last step, or "fine-tuning" capability for a user who has dettermined a set of model parameters for a specific device. Comparison of device test data curves or other CAD values to mathematical performance curves generated by EQSOLVE or any general modeling software package (ECAP, SCEPTRE, SPICE, etc.) will produce curve differences similar to the curve differences on one or several of the curve sets contained in this appendix. The user then has insight on the erroneous parameter(s).

## B.1 $I_B$ vs. $V_{BE}$ Curves

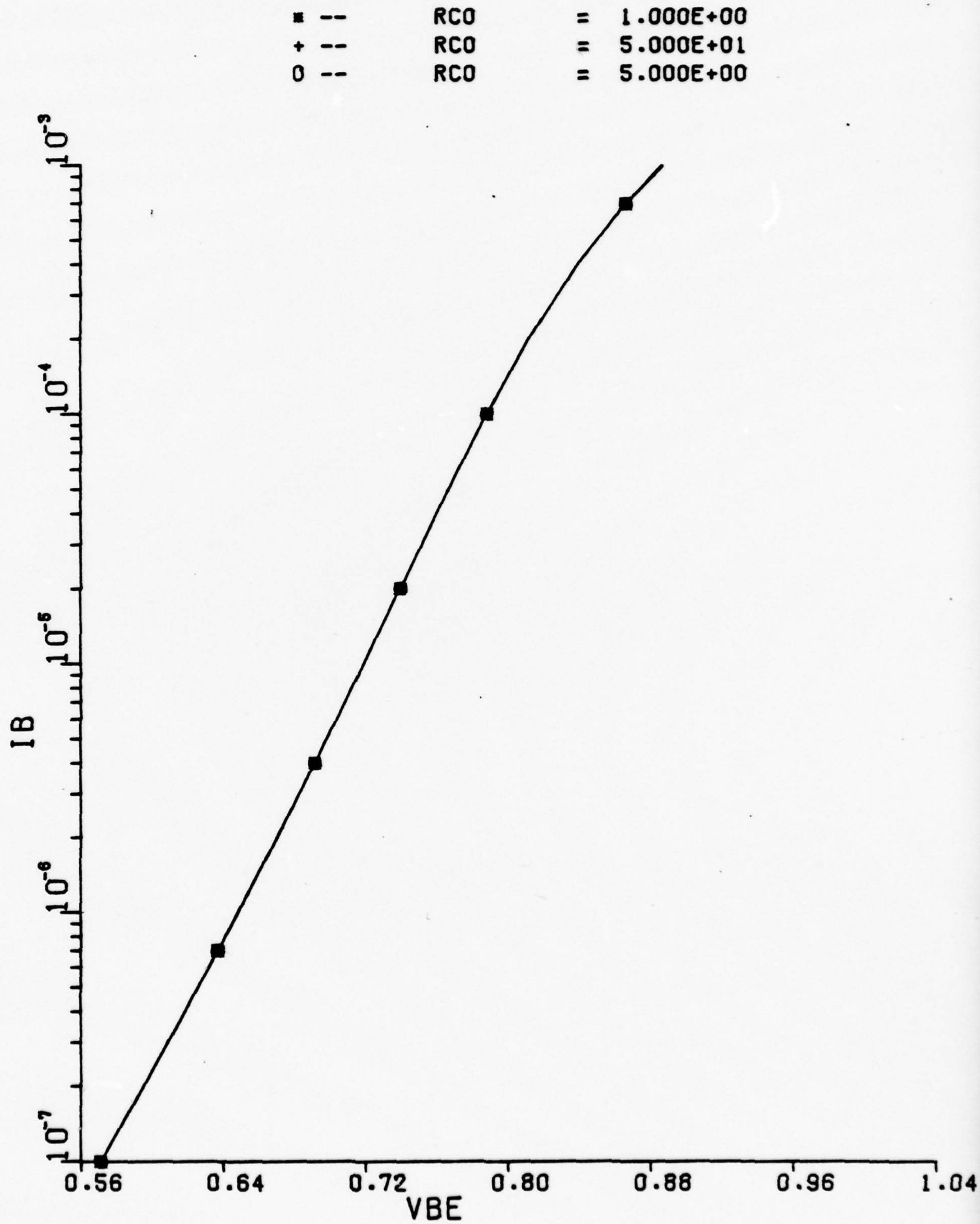

* -- RBO = 9.000E+01
+ -- RBO = 9.000E-01
0 -- RBO = 9.000E+00
IB
VBE
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04



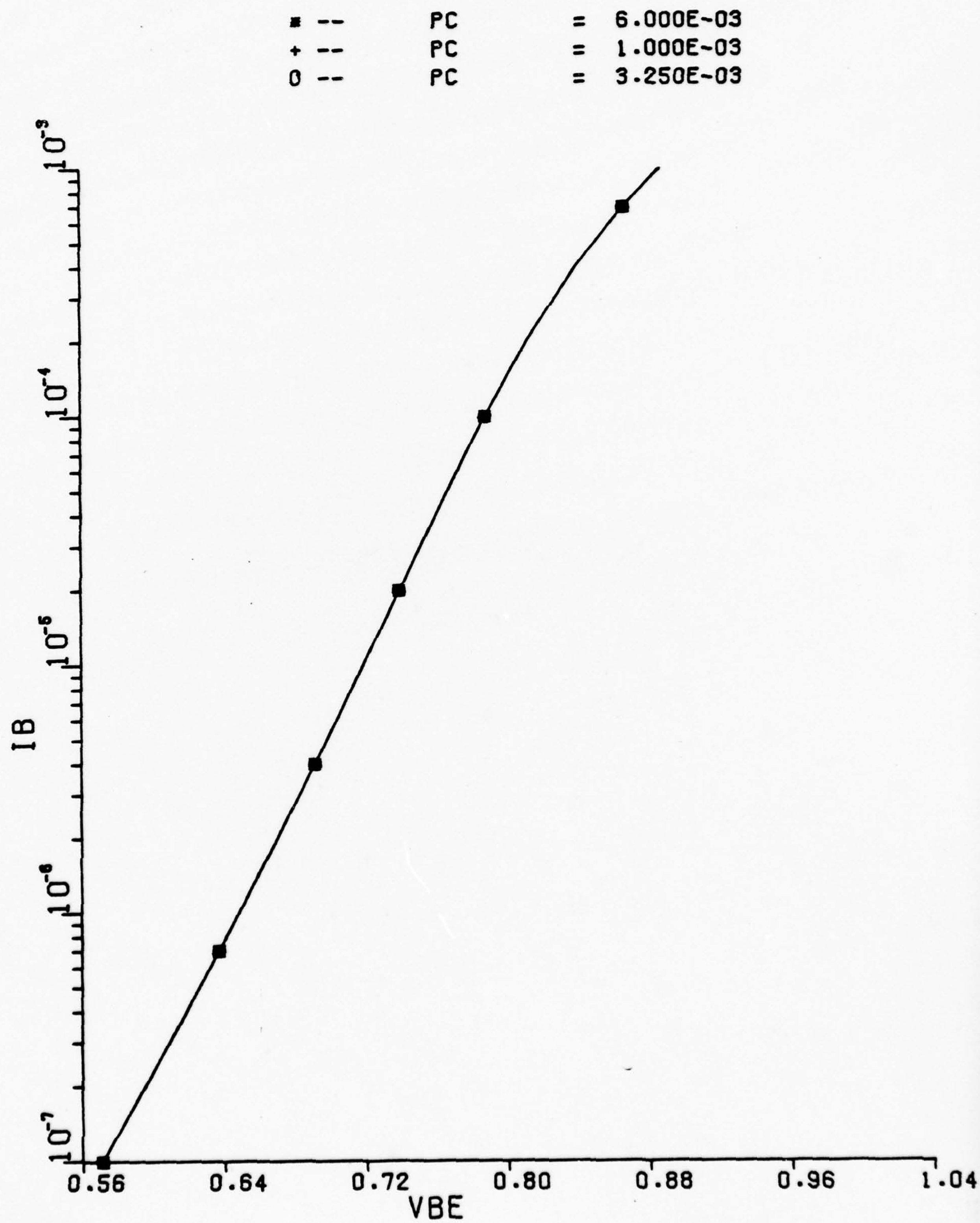
* -- RBB = 1.500E+01
+ -- RBB = 5.000E+02
0 -- RBB = 1.500E+02
IB
VBE
0.48
0.56
0.64
0.72
0.80
0.88
0.96



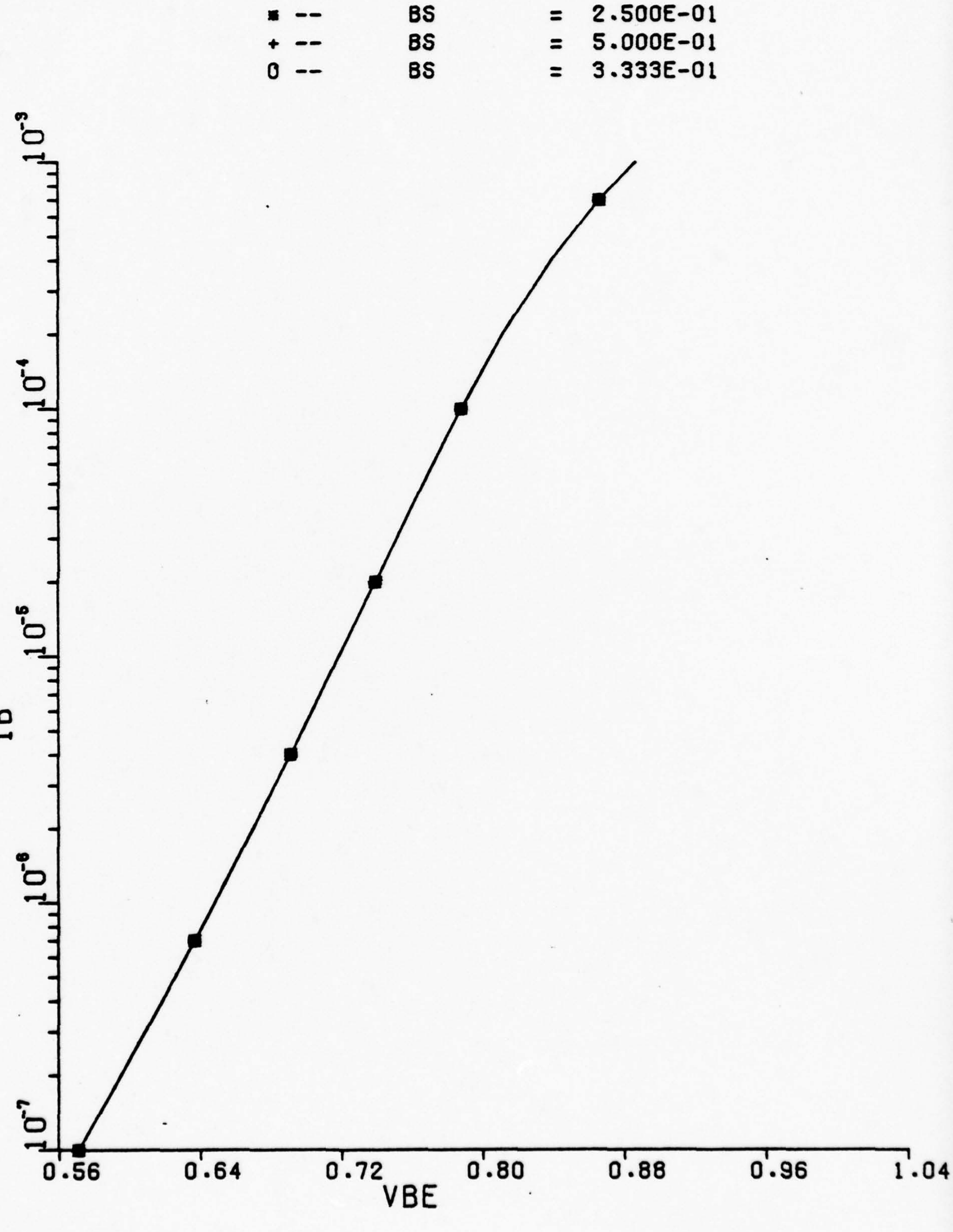
* -- RE = 1.000E-02
+ -- RE = 5.000E+00
O -- RE = 5.000E-01
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.50
0.60
0.70
0.80
0.90
1.00
1.10
VBE

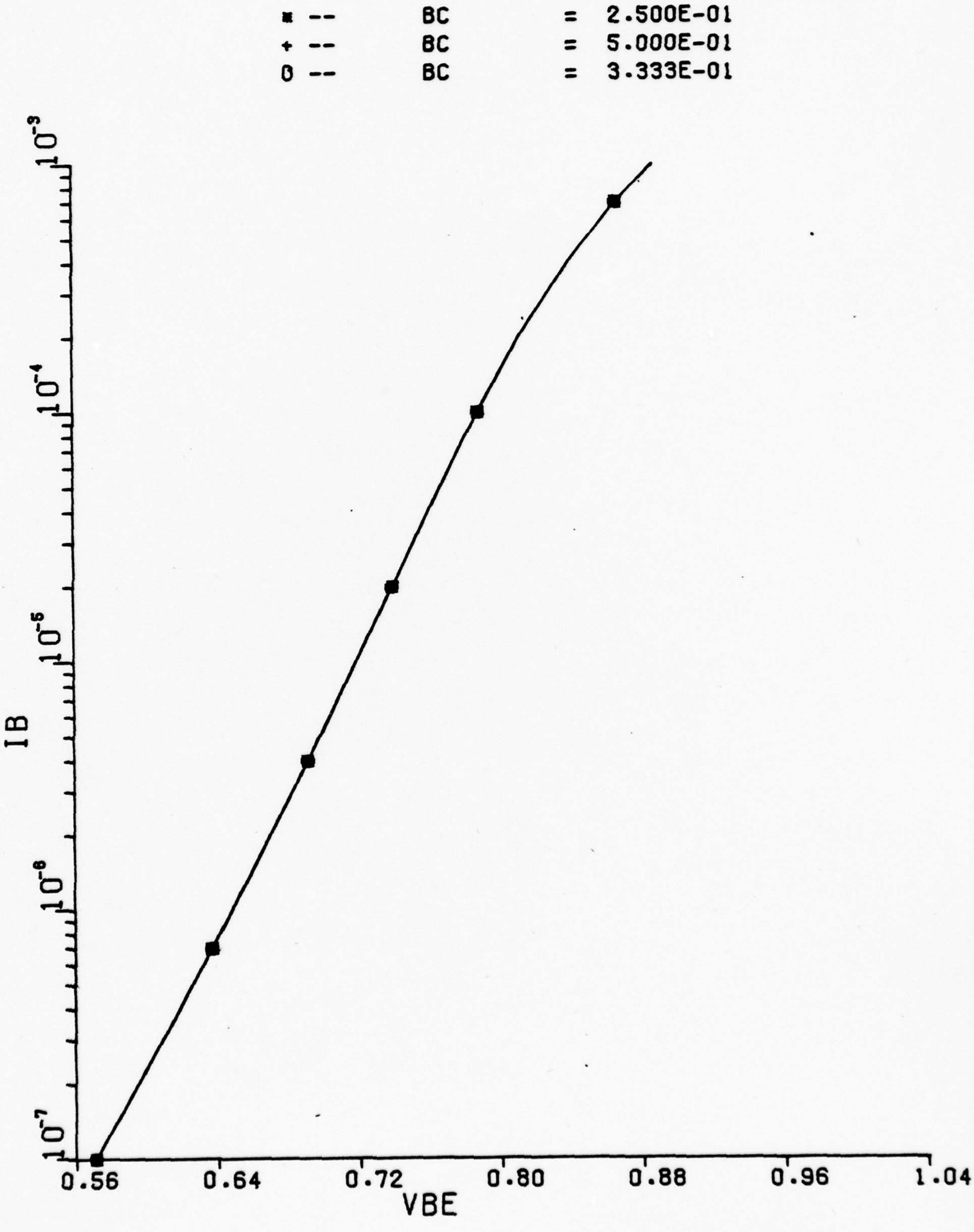


* -- RCO = 1.000E+00
+ -- RCO = 5.000E+01
0 -- RCO = 5.000E+00
IB
VBE
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
0.56
0.64
0.72
0.80
0.88
0.96
1.04

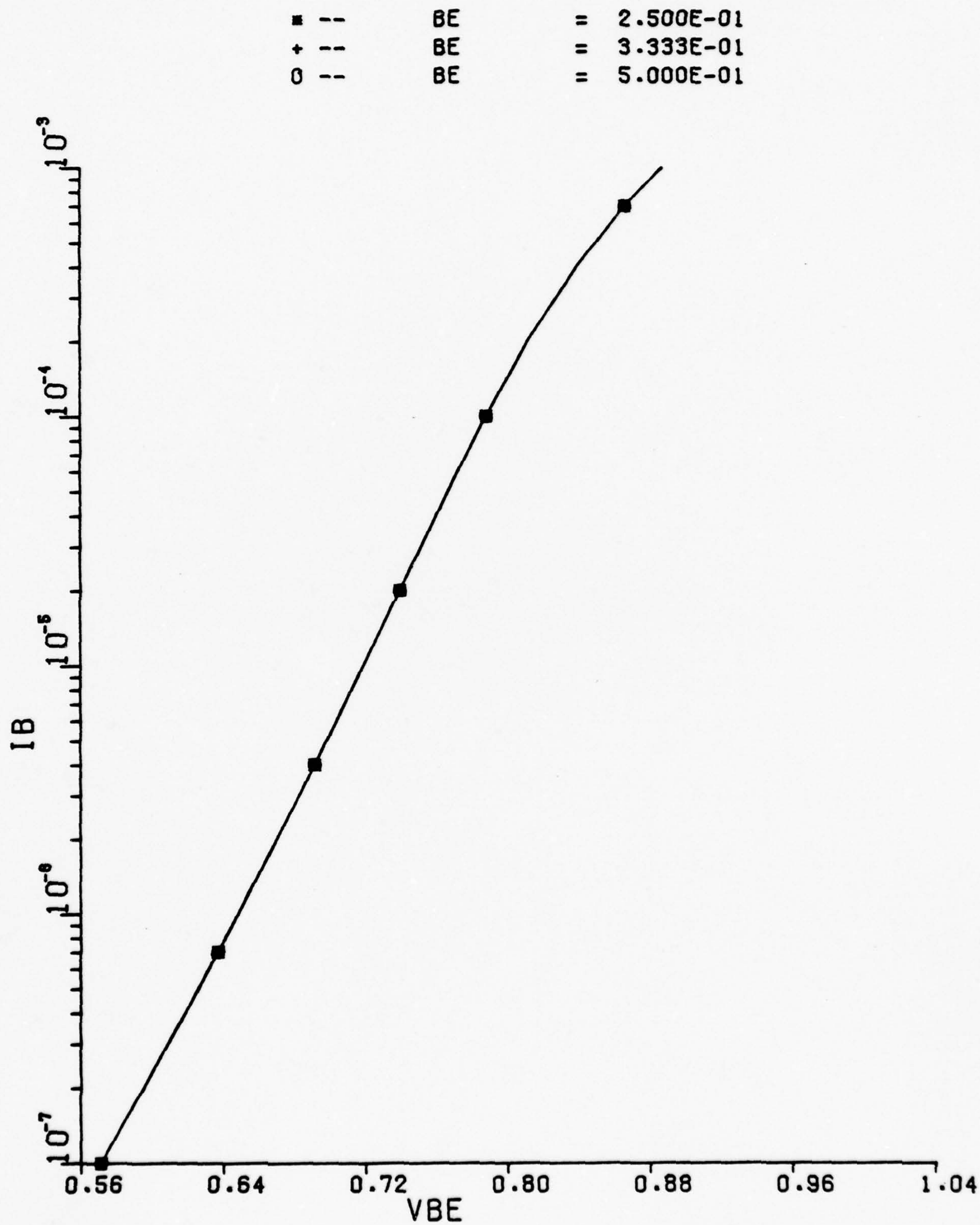


* -- PC = 6.000E-03
+ -- PC = 1.000E-03
0 -- PC = 3.250E-03
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

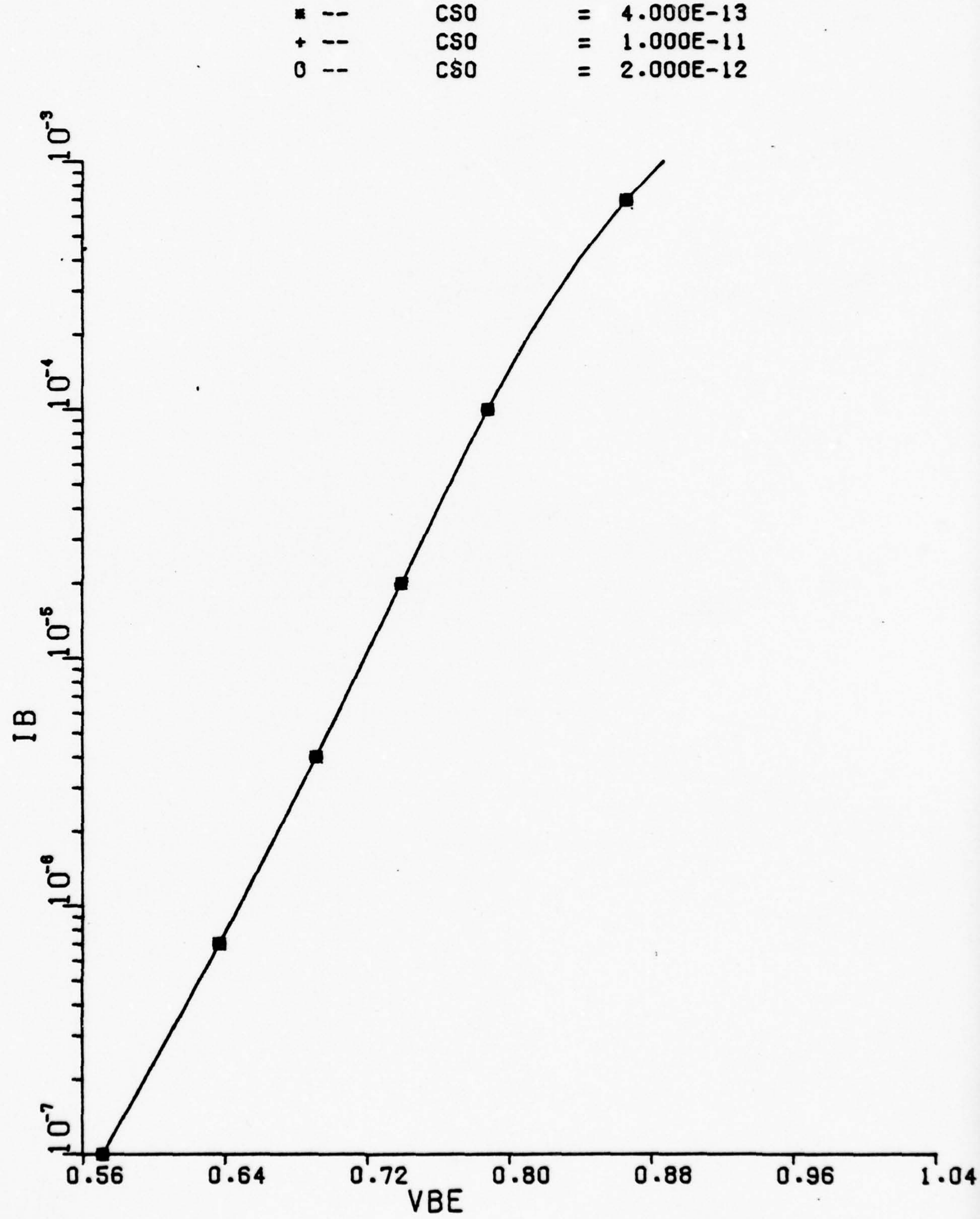

* -- BS = 2.500E-01
+ -- BS = 5.000E-01
0 -- BS = 3.333E-01
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



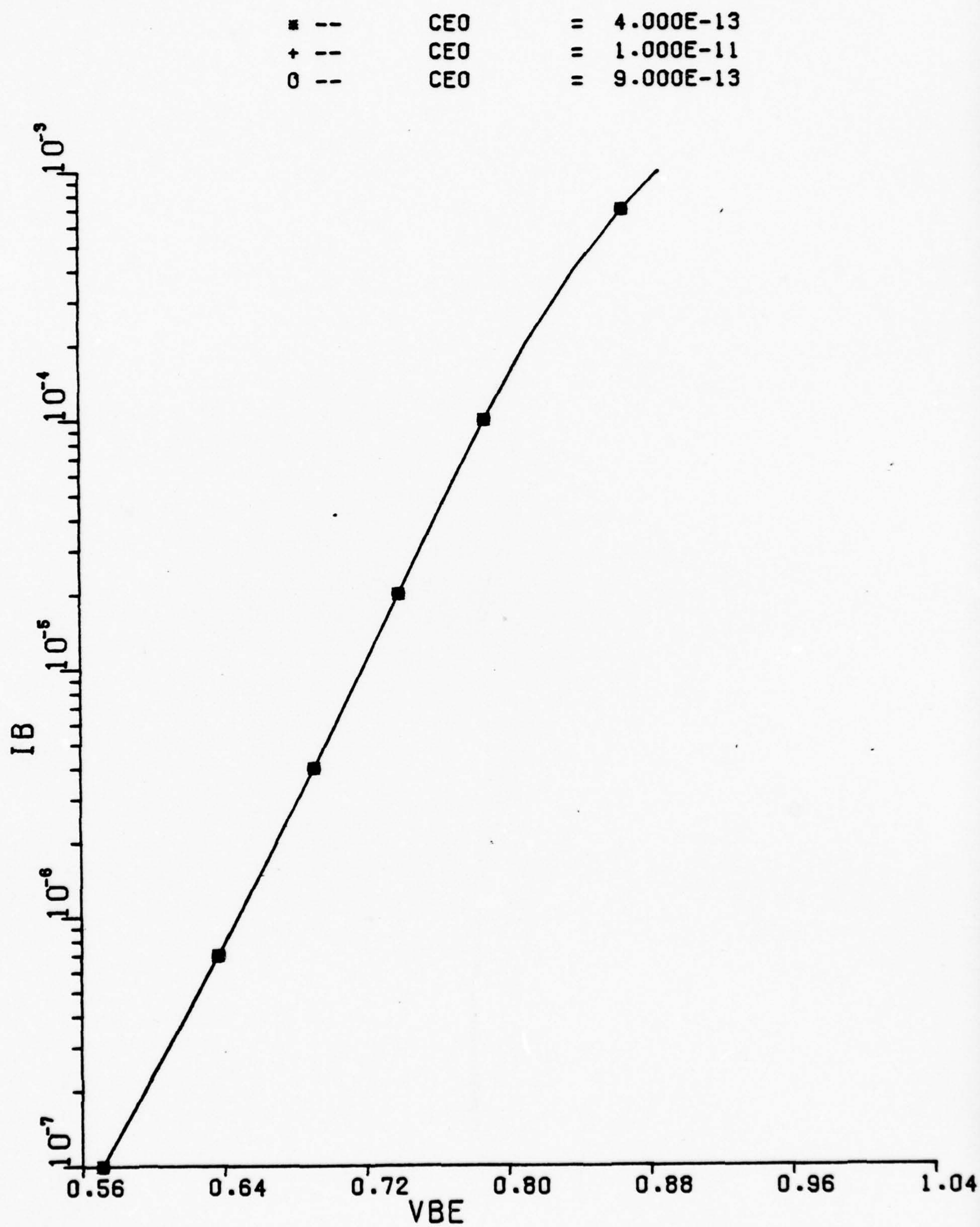
* -- BC = 2.500E-01
+ -- BC = 5.000E-01
0 -- BC = 3.333E-01
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

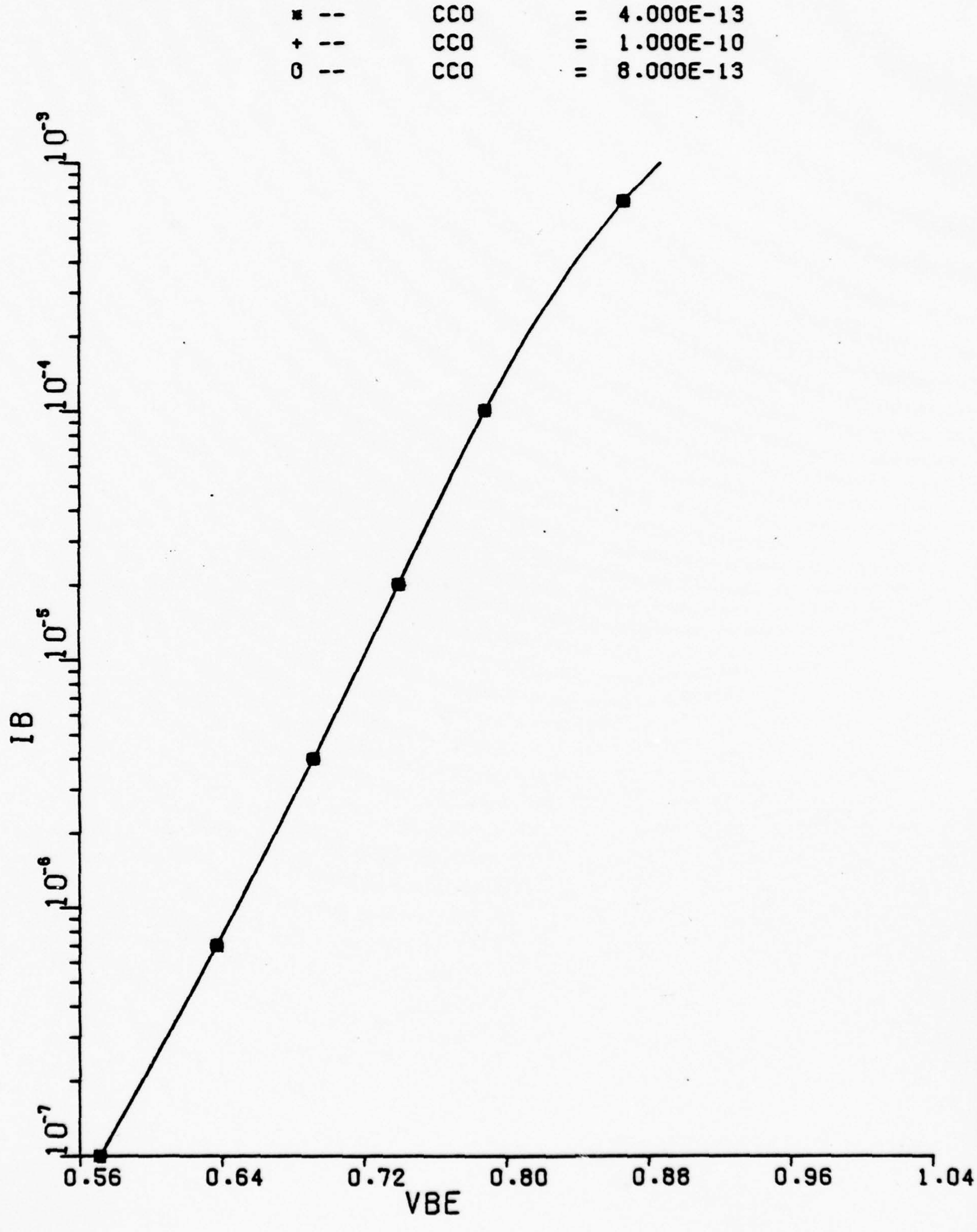


■ -- BE = 2.500E-01
+ -- BE = 3.333E-01
0 -- BE = 5.000E-01
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

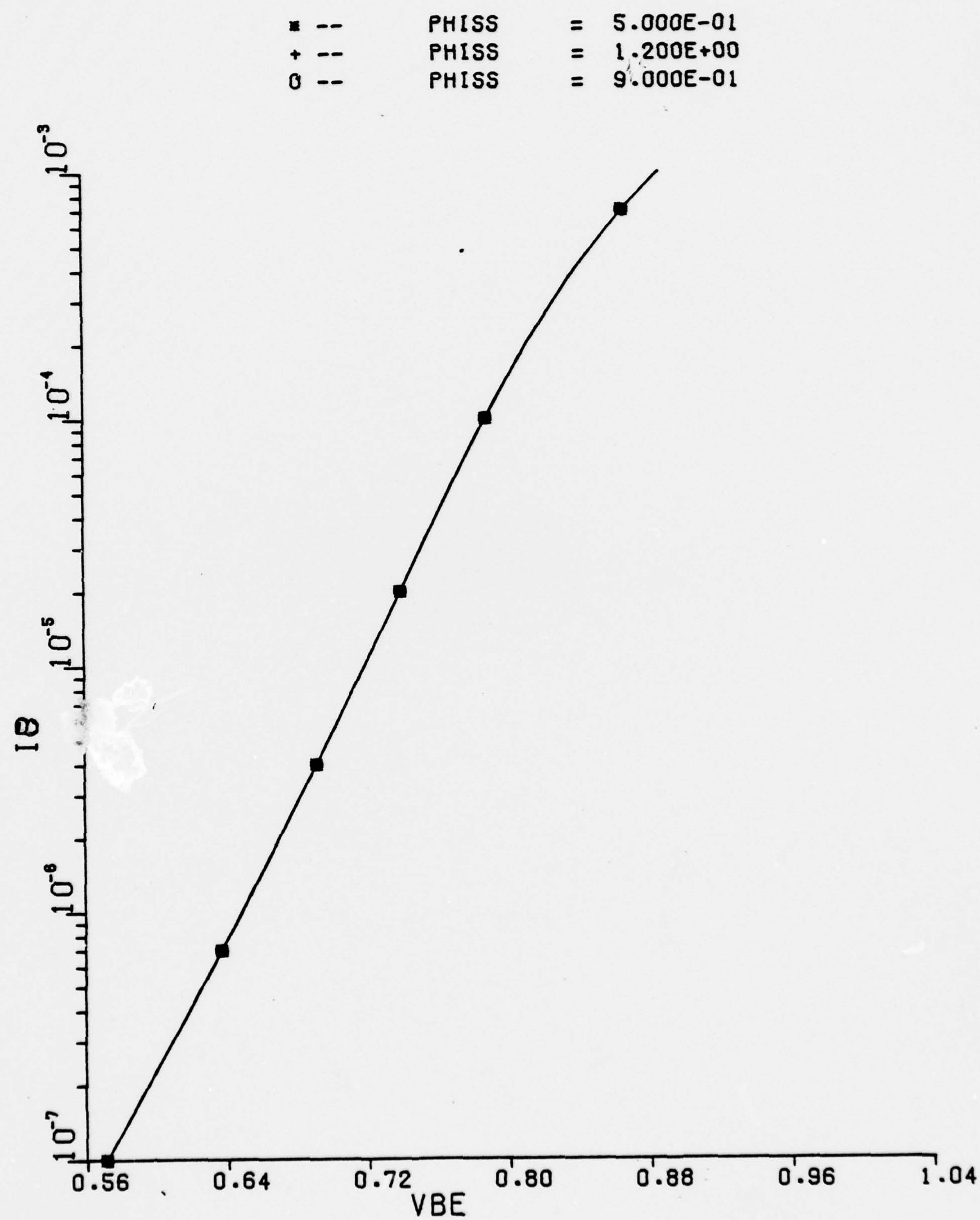


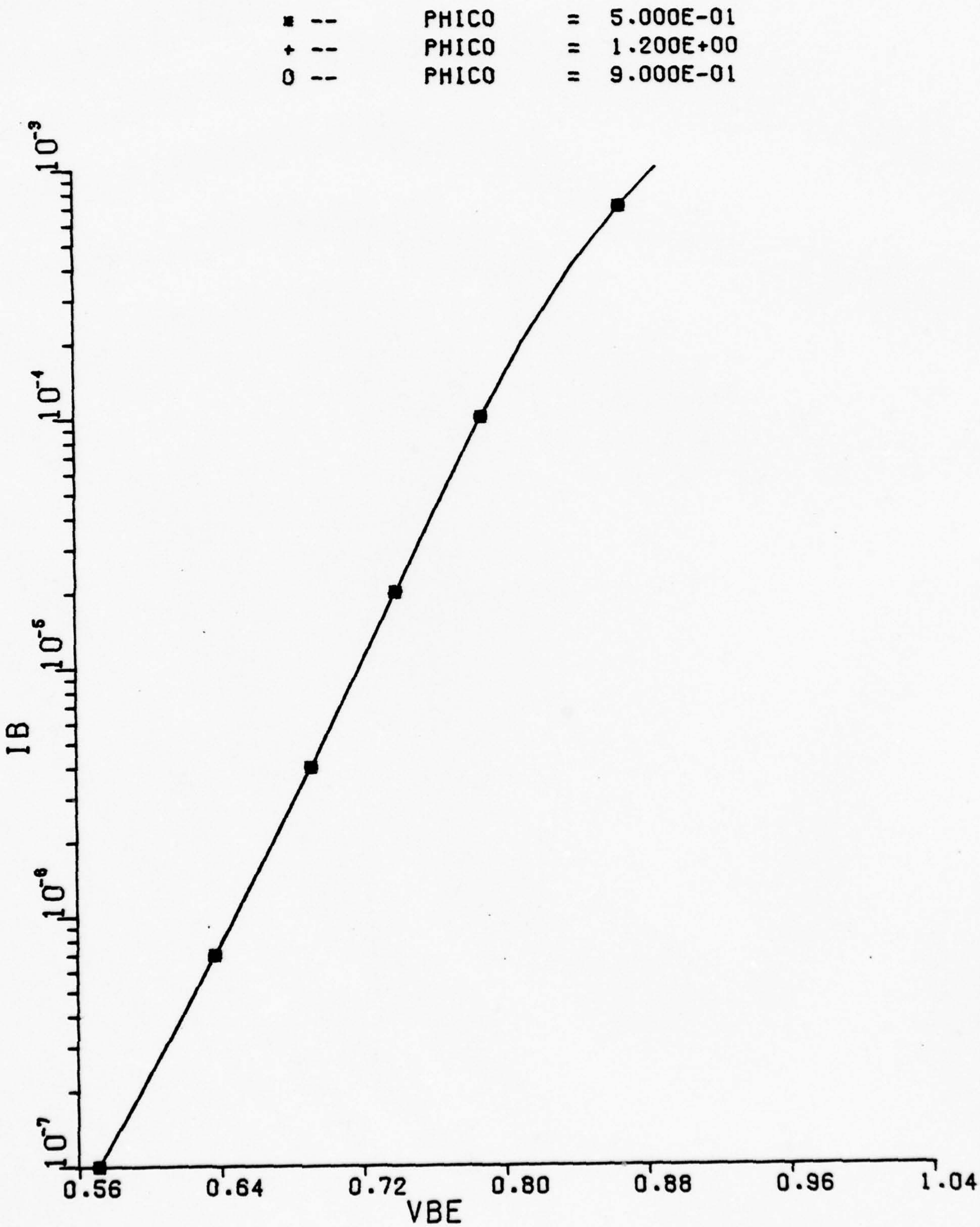
* -- CSO = 4.000E-13
+ -- CSO = 1.000E-11
0 -- CSO = 2.000E-12
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE


* -- CEO = 4.000E-13
+ -- CEO = 1.000E-11
0 -- CEO = 9.000E-13
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

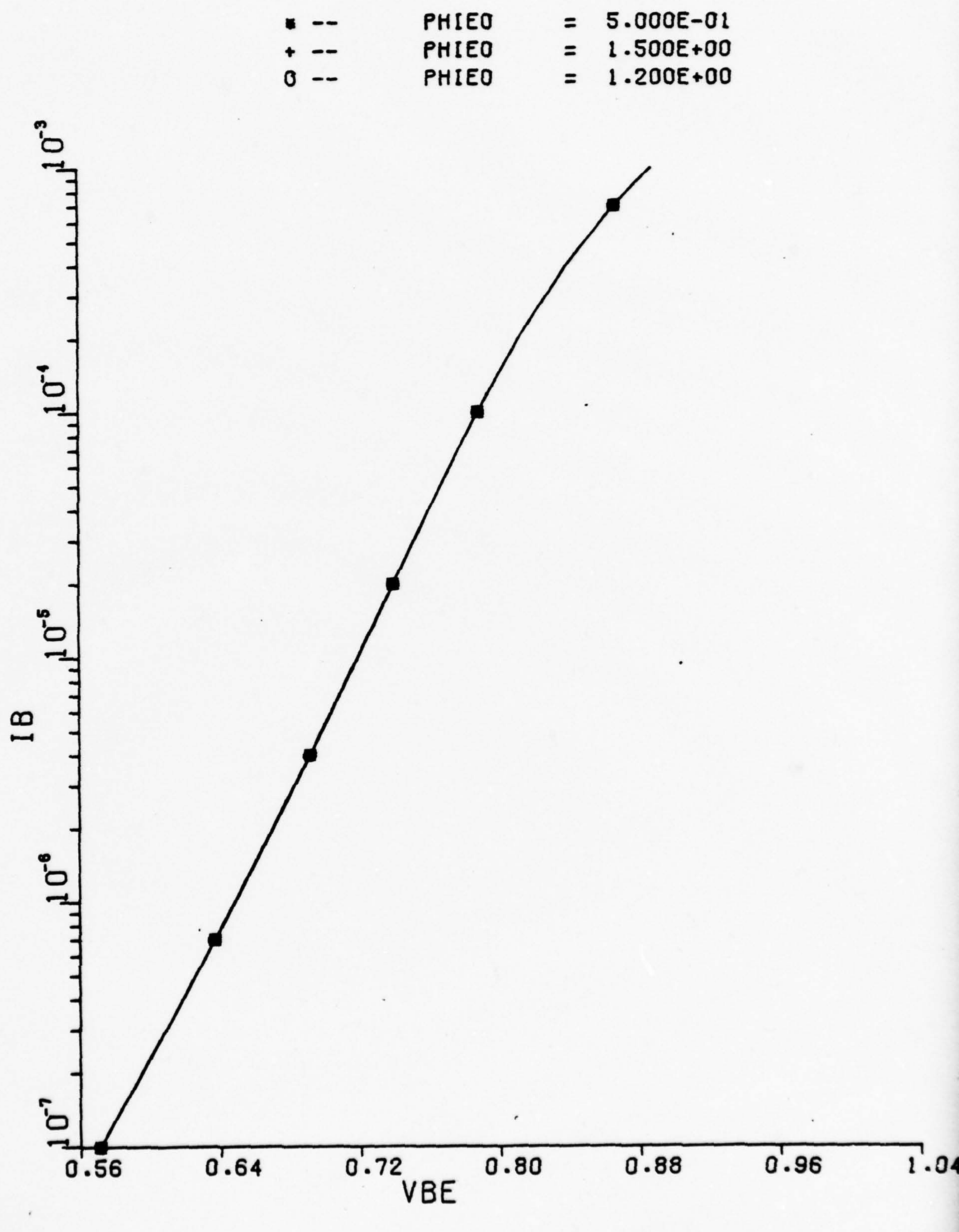


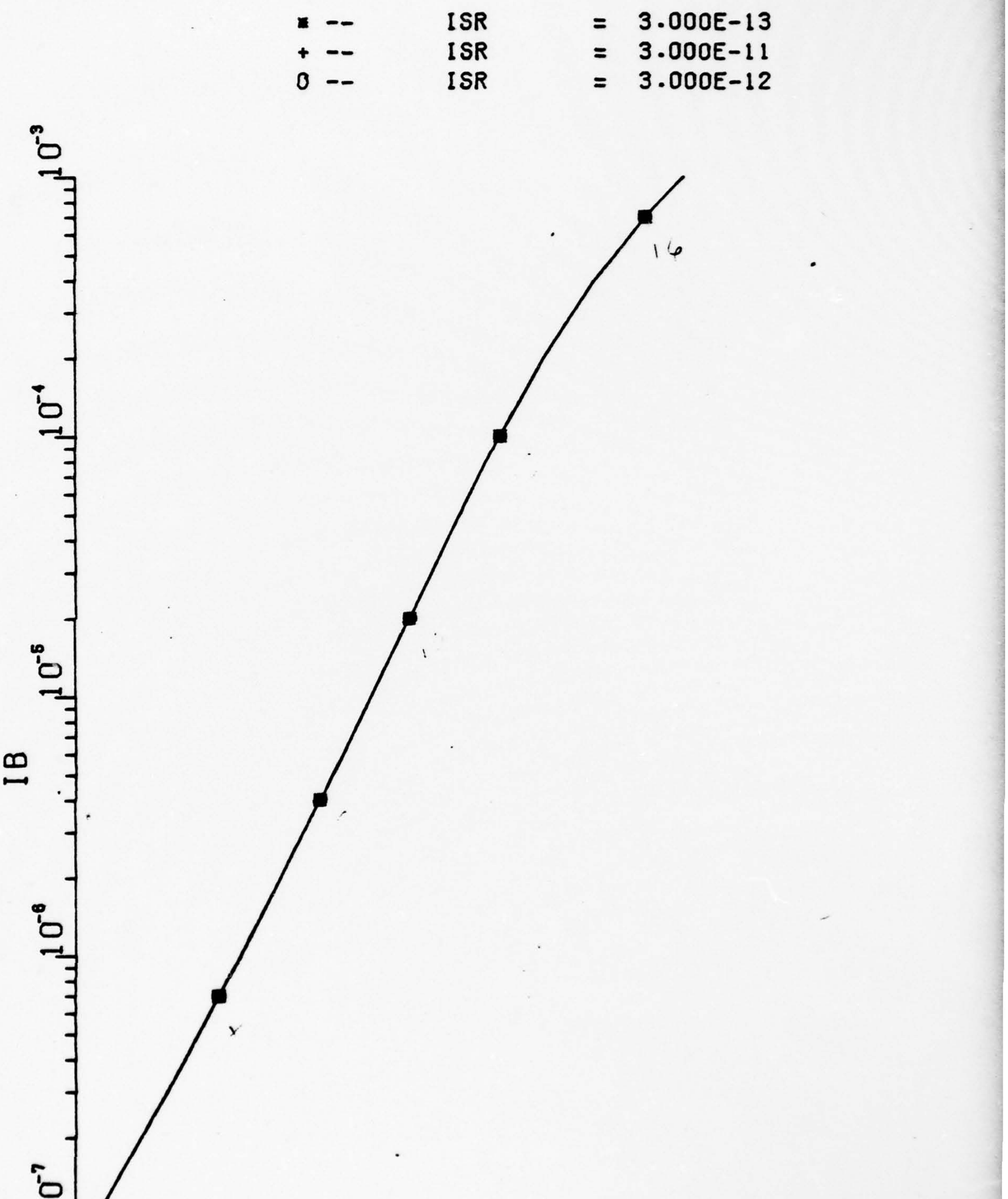
* -- CCO = 4.000E-13
+ -- CCO = 1.000E-10
0 -- CCO = 8.000E-13
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04


* -- PHISS = 5.000E-01
+ -- PHISS = 1.200E+00
0 -- PHISS = 9.000E-01
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

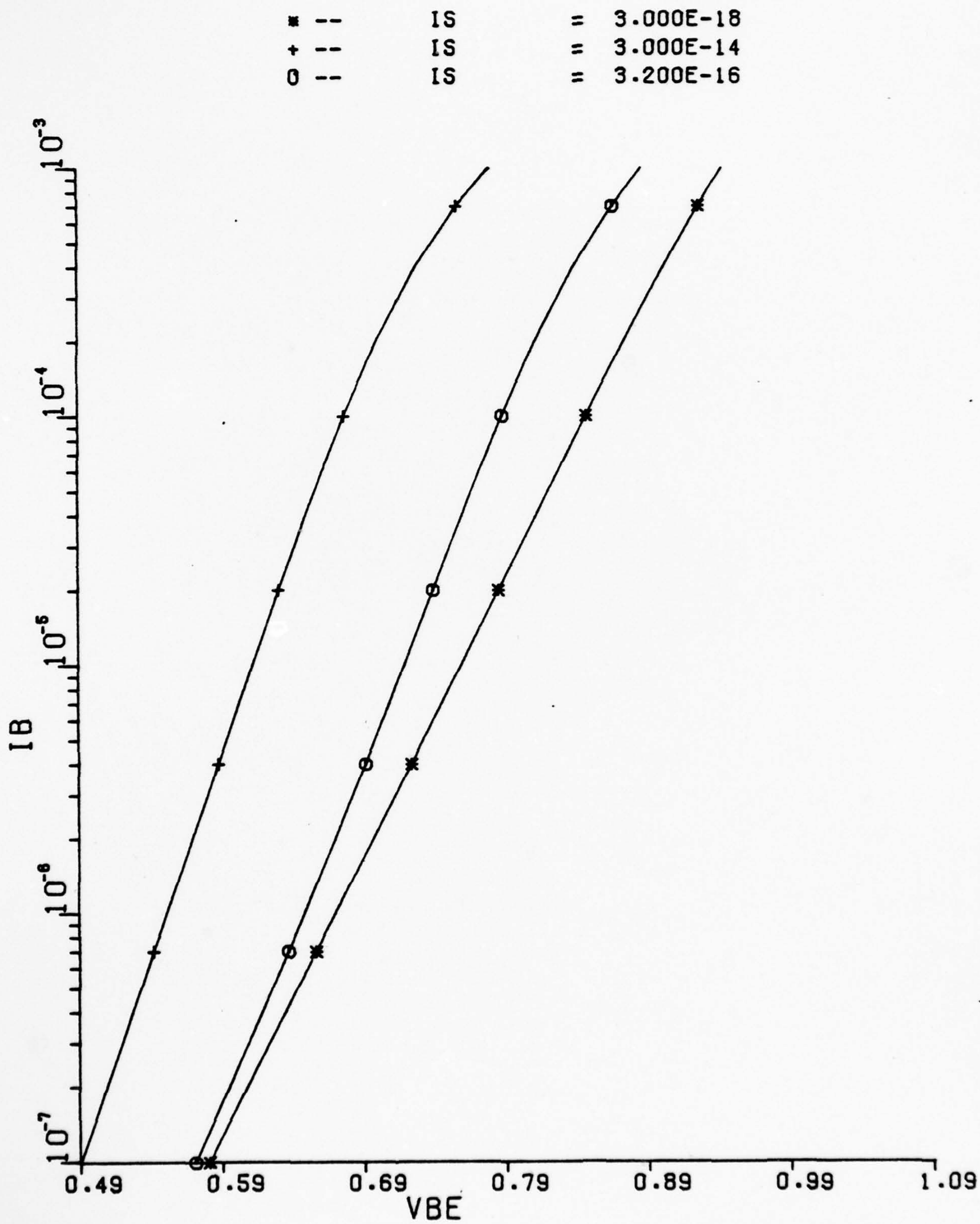


* -- PHICO = 5.000E-01
+ -- PHICO = 1.200E+00
0 -- PHICO = 9.000E-01
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

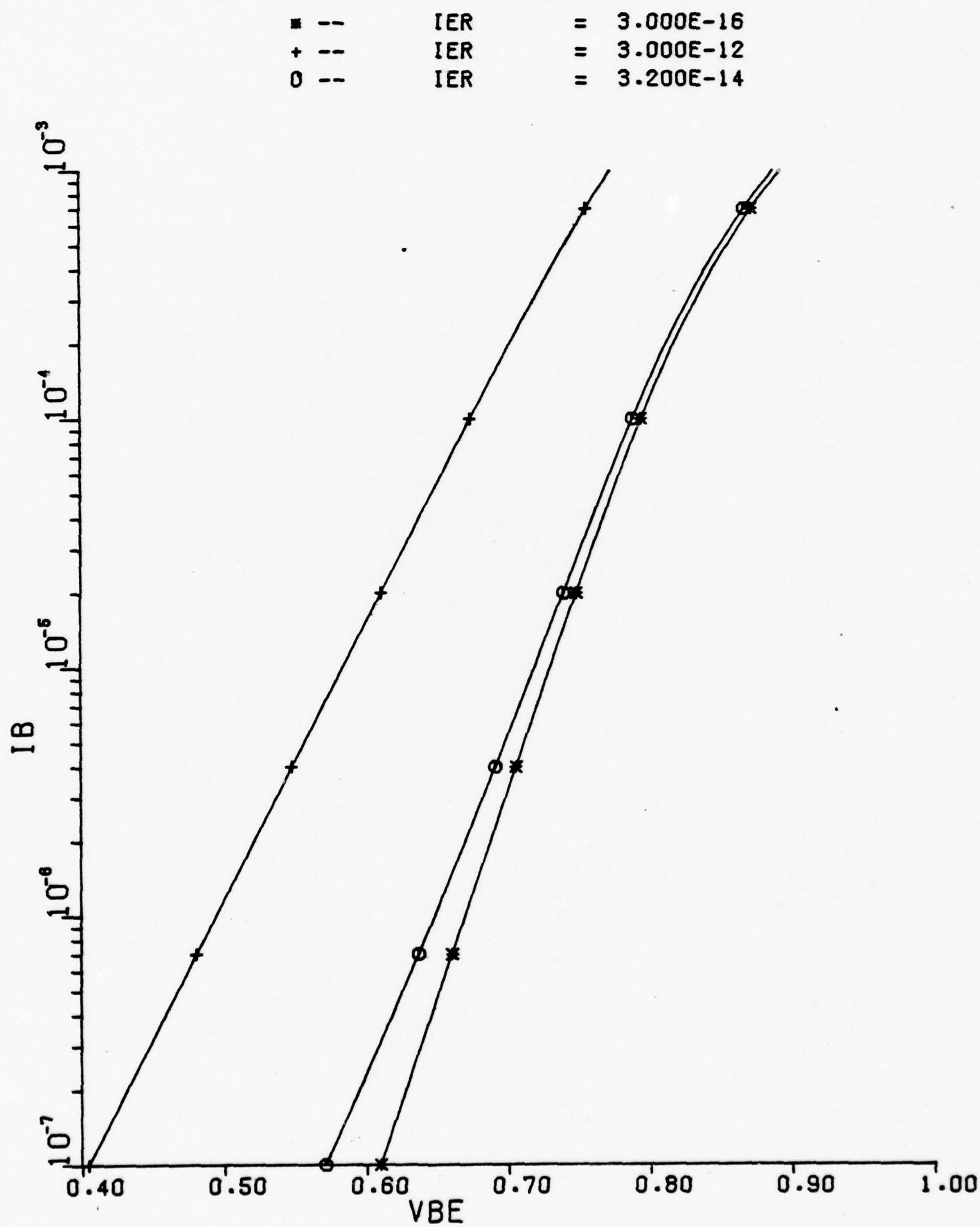

* -- PHIEO = 5.000E-01
+ -- PHIEO = 1.500E+00
O -- PHIEO = 1.200E+00
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



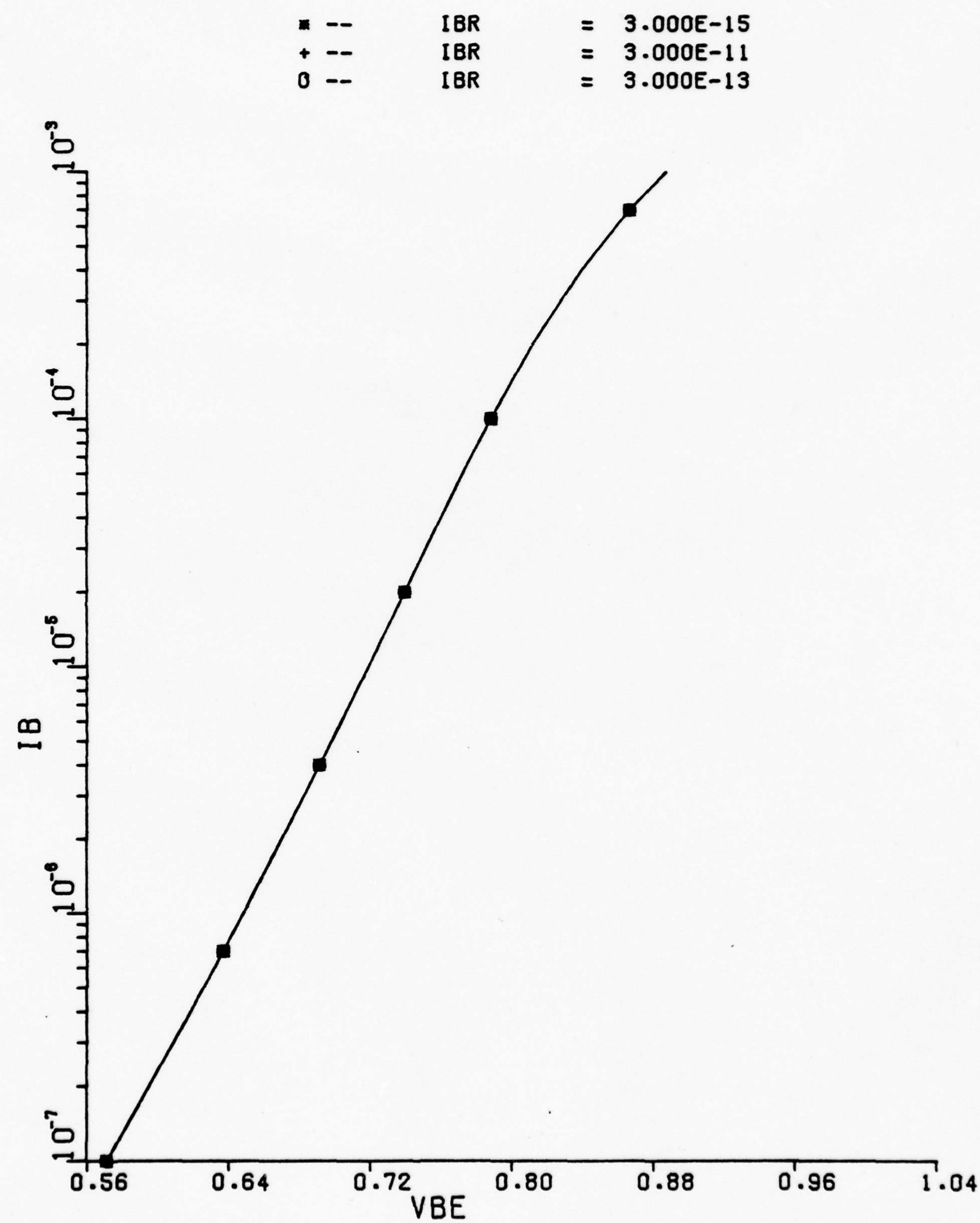
■ -- ISR = 3.000E-13
+ -- ISR = 3.000E-11
0 -- ISR = 3.000E-12
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.0
VBE
16



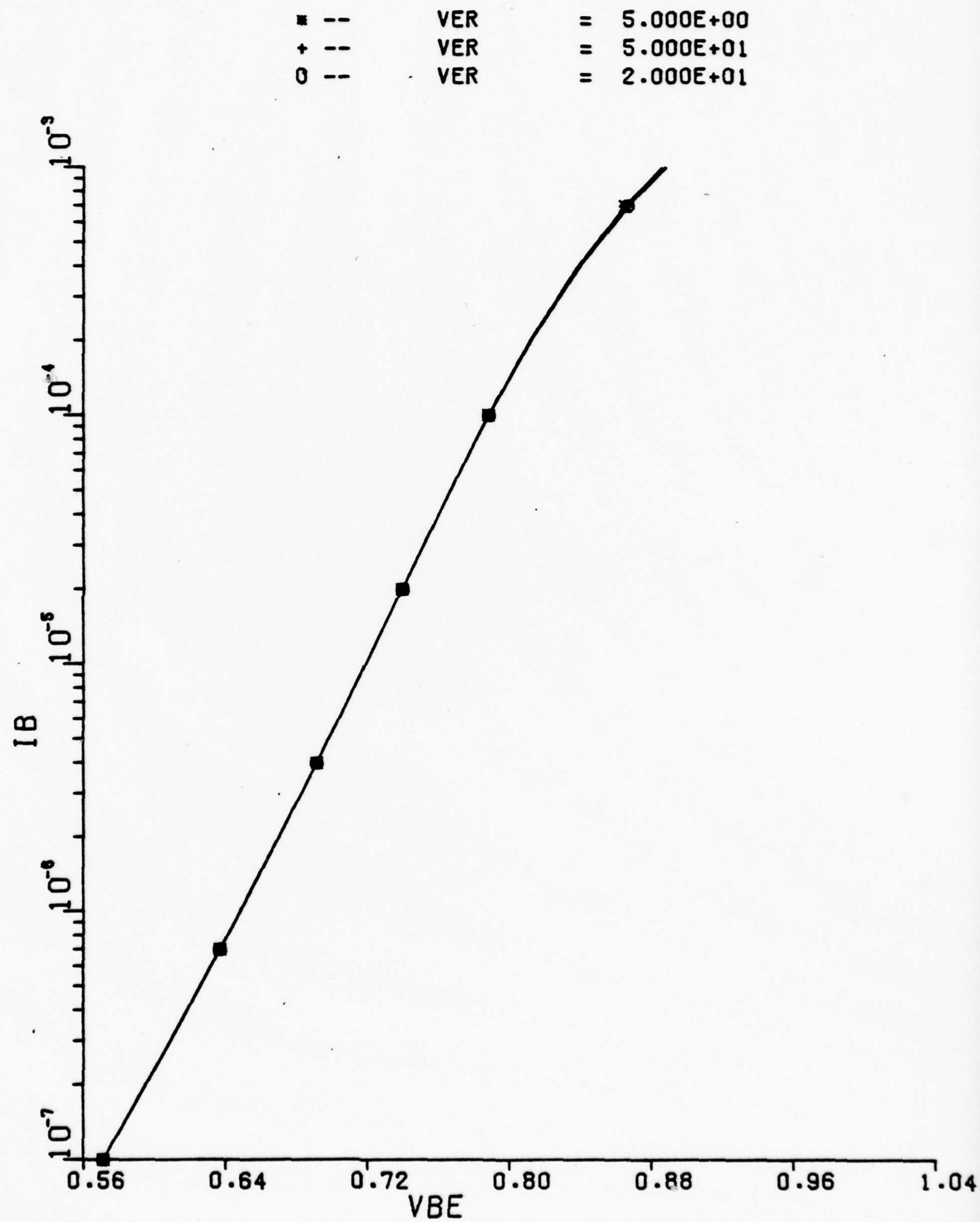
* -- IS = 3.000E-18
+ -- IS = 3.000E-14
0 -- IS = 3.200E-16
IB
VBE
0.49
0.59
0.69
0.79
0.89
0.99
1.09



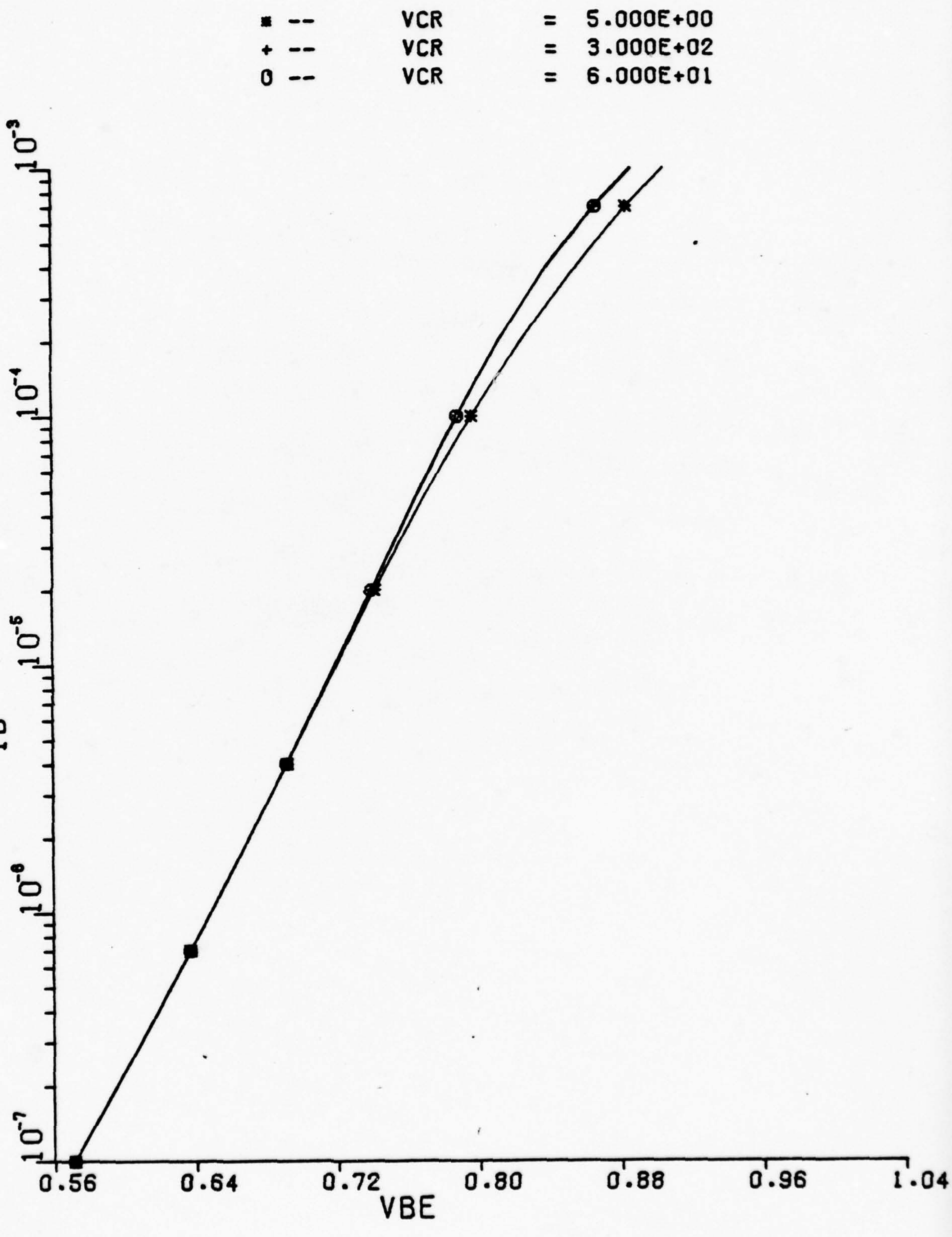
* -- IER = 3.000E-16
+ -- IER = 3.000E-12
0 -- IER = 3.200E-14
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.40
0.50
0.60
0.70
0.80
0.90
1.00
VBE



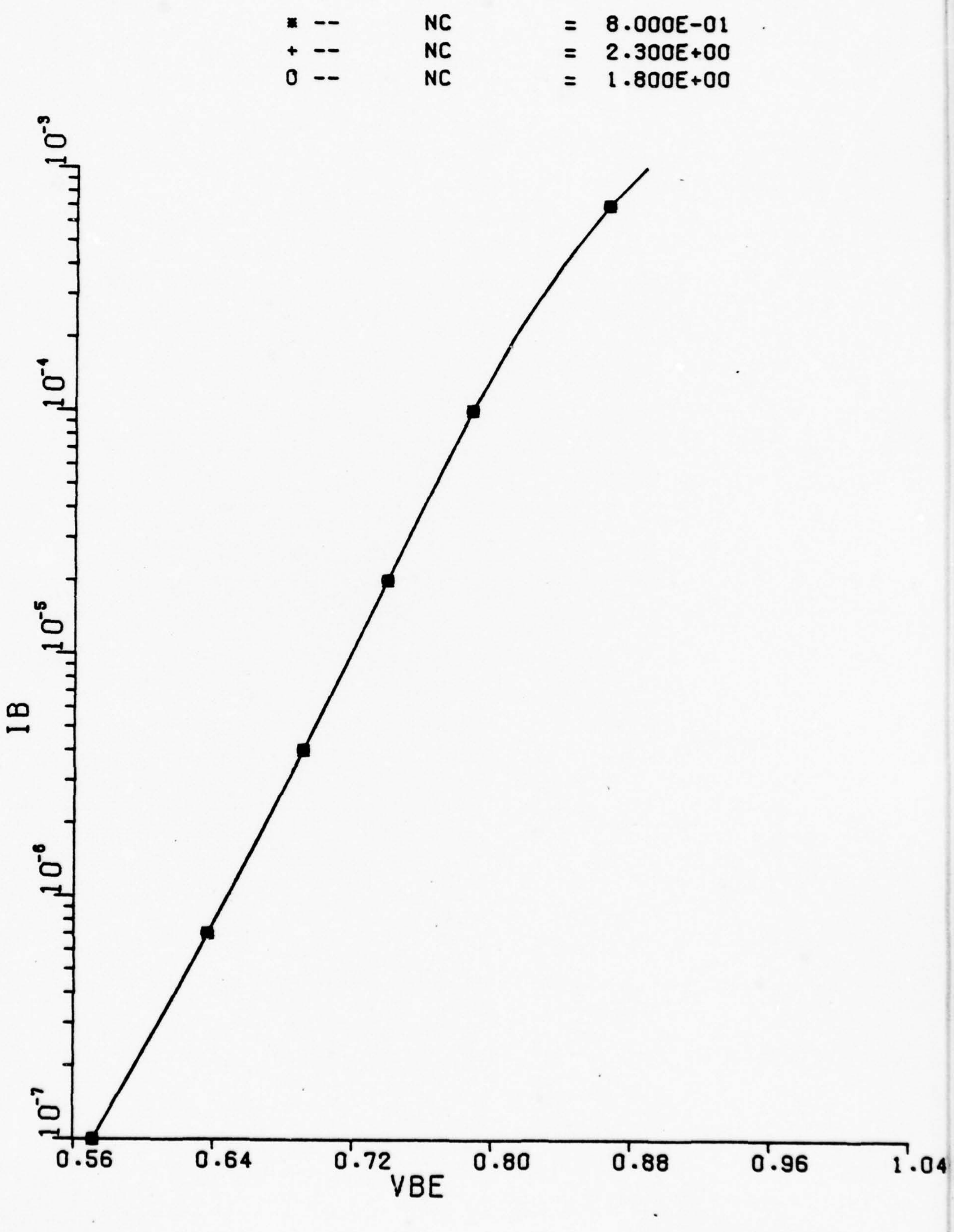
* -- IBR = 3.000E-15
+ -- IBR = 3.000E-11
0 -- IBR = 3.000E-13
IB
VBE
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04



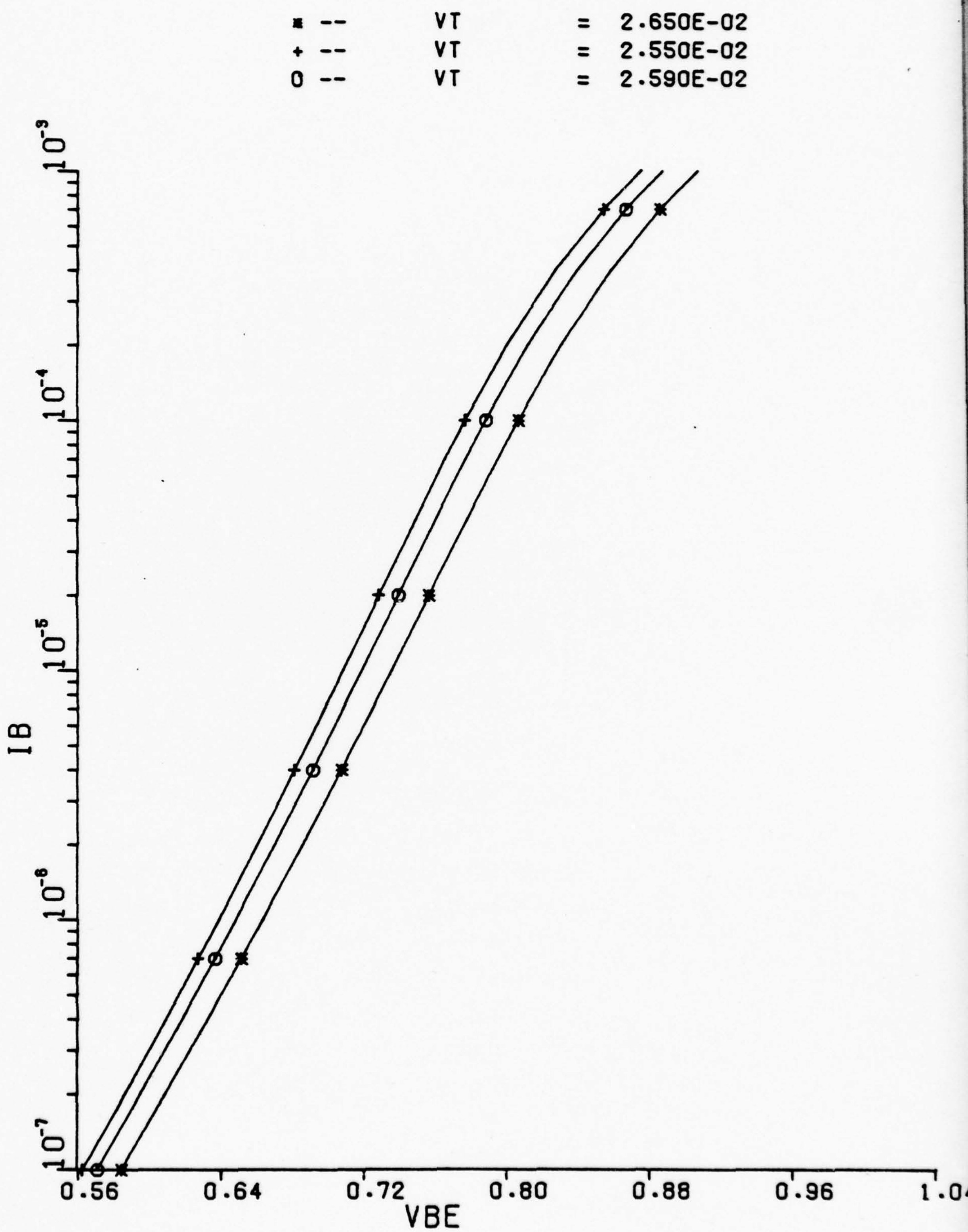
* -- VER = 5.000E+00
+ -- VER = 5.000E+01
0 -- VER = 2.000E+01
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

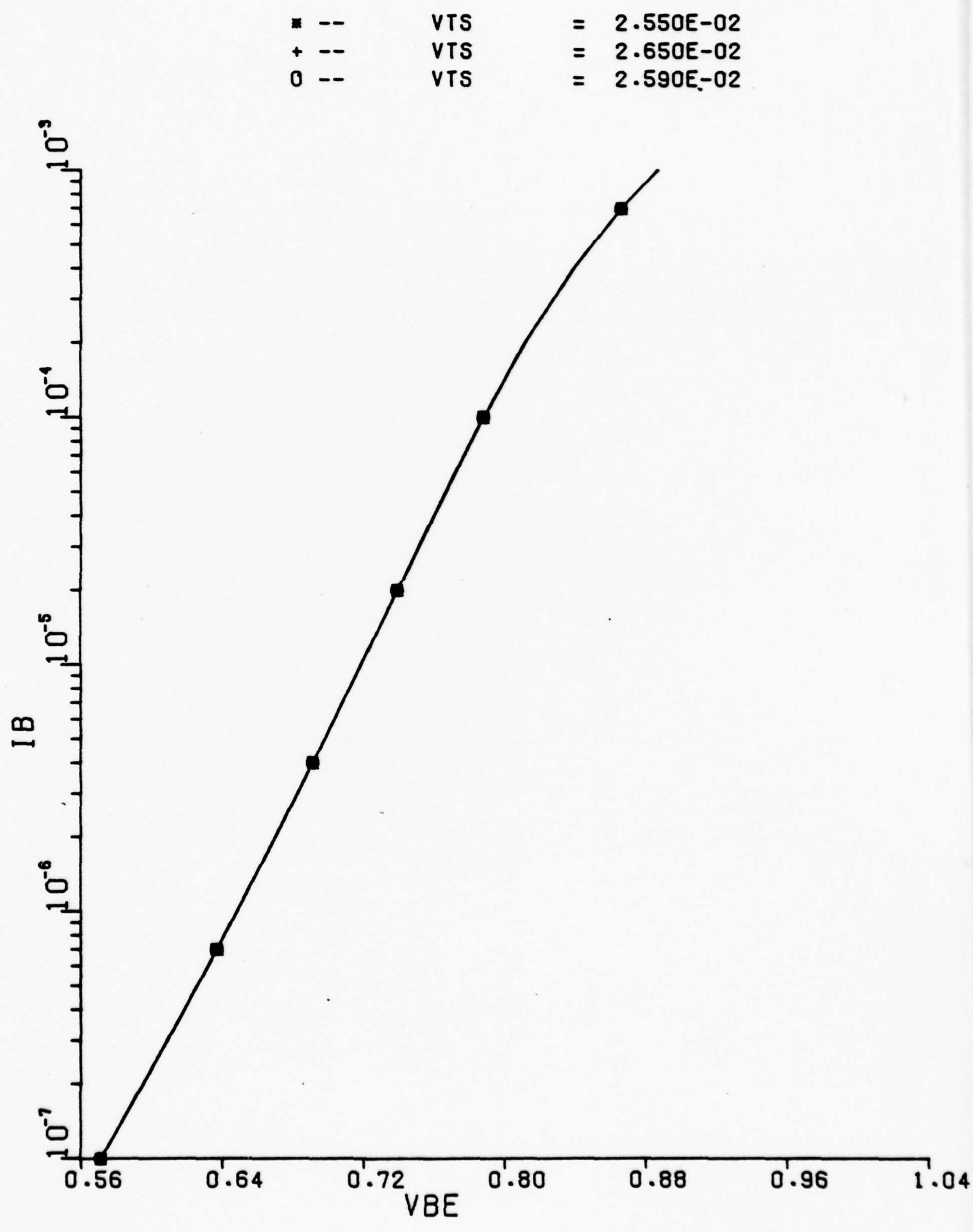


* -- VCR = 5.000E+00
+ -- VCR = 3.000E+02
0 -- VCR = 6.000E+01
IB
10^-3
10^-4
10^-5
10^-6
10^-7
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

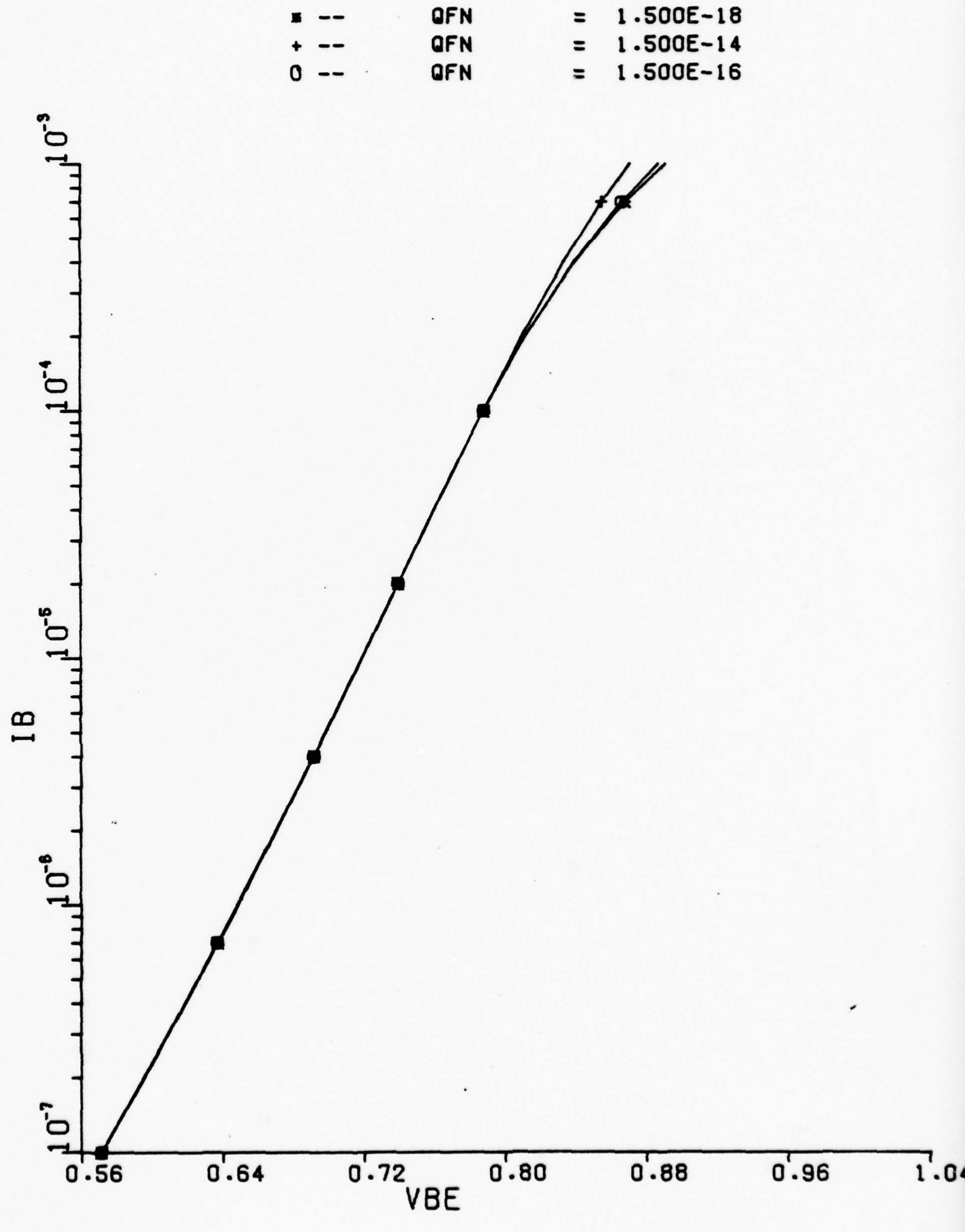


* -- NC = 8.000E-01
+ -- NC = 2.300E+00
0 -- NC = 1.800E+00
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

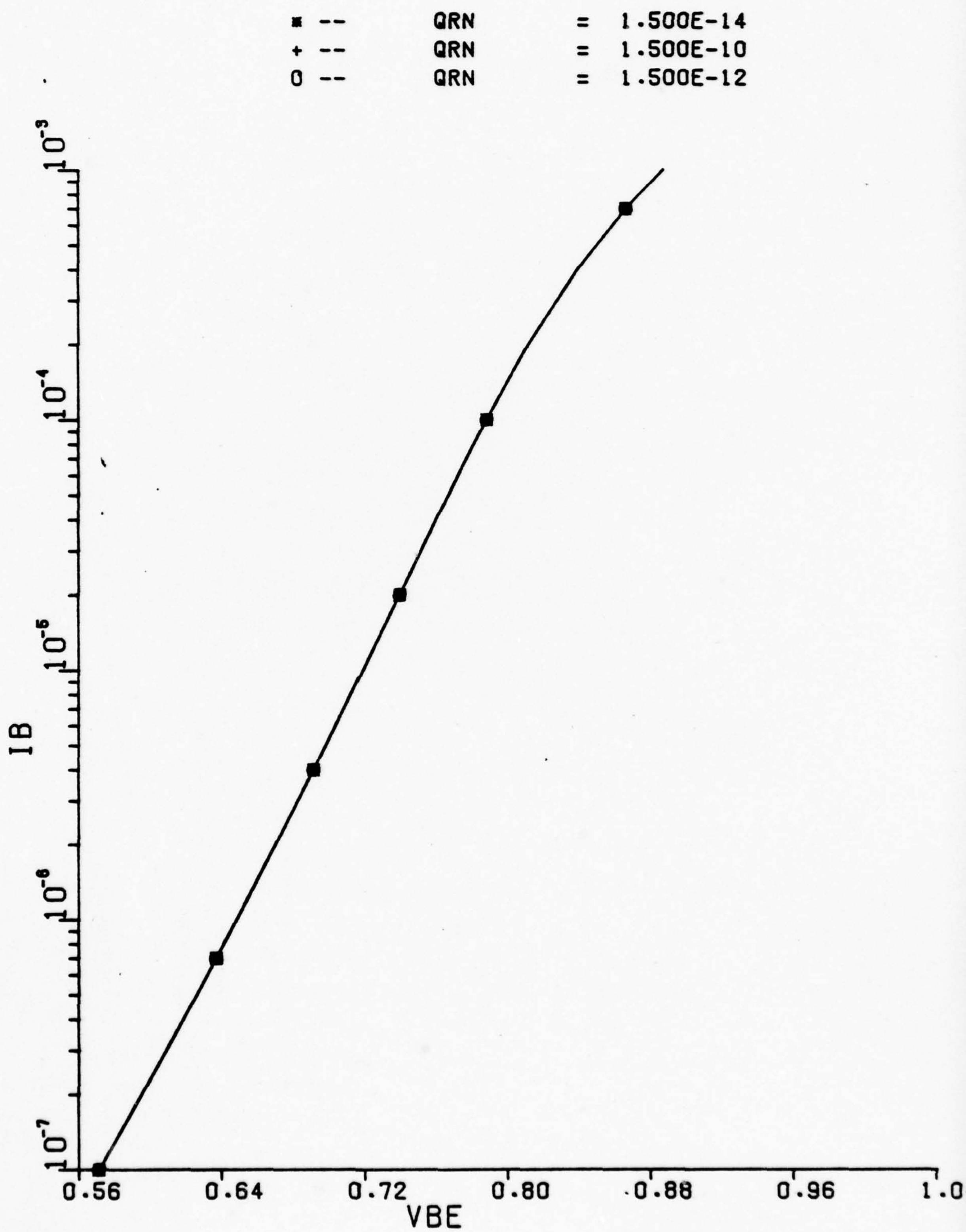

* -- VT = 2.650E-02
+ -- VT = 2.550E-02
0 -- VT = 2.590E-02
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

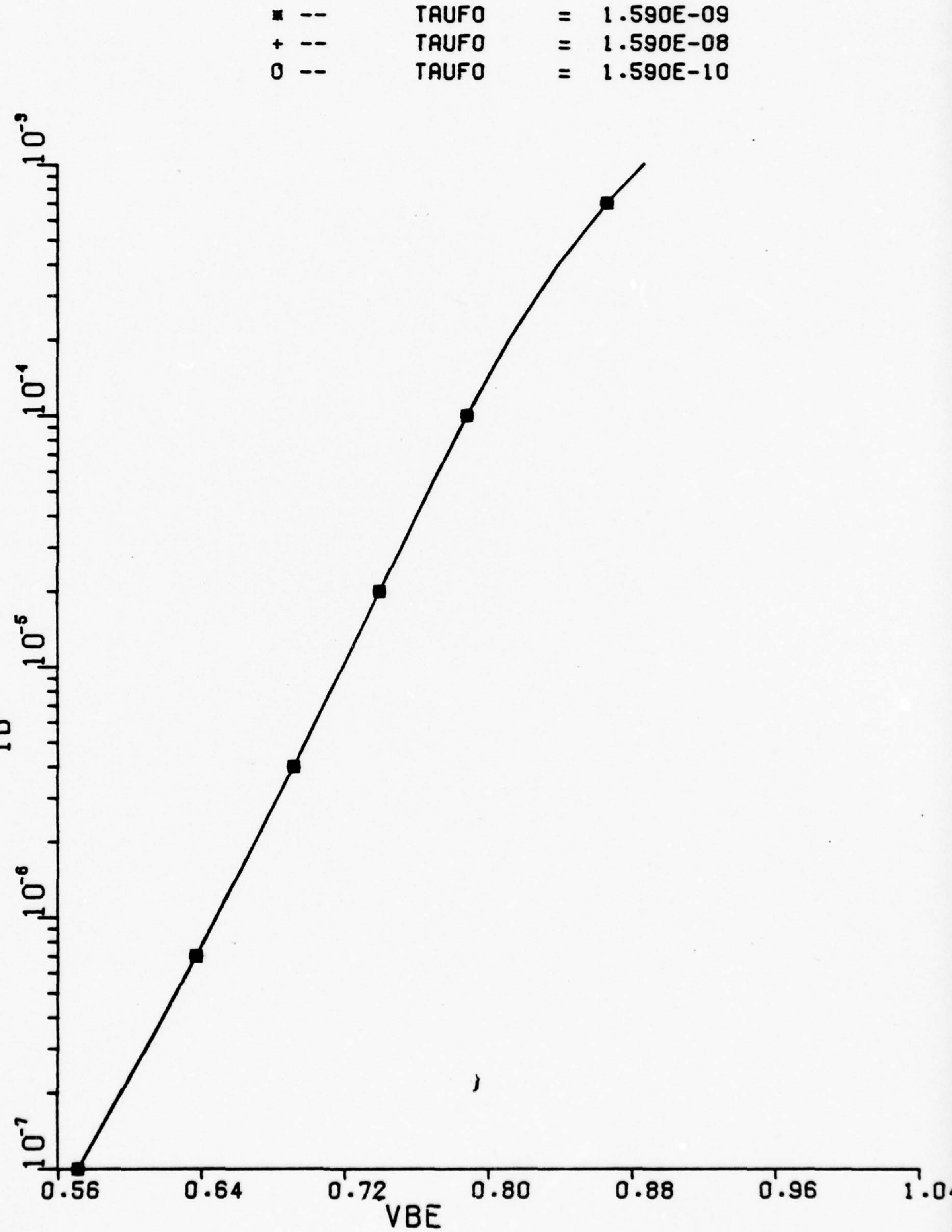


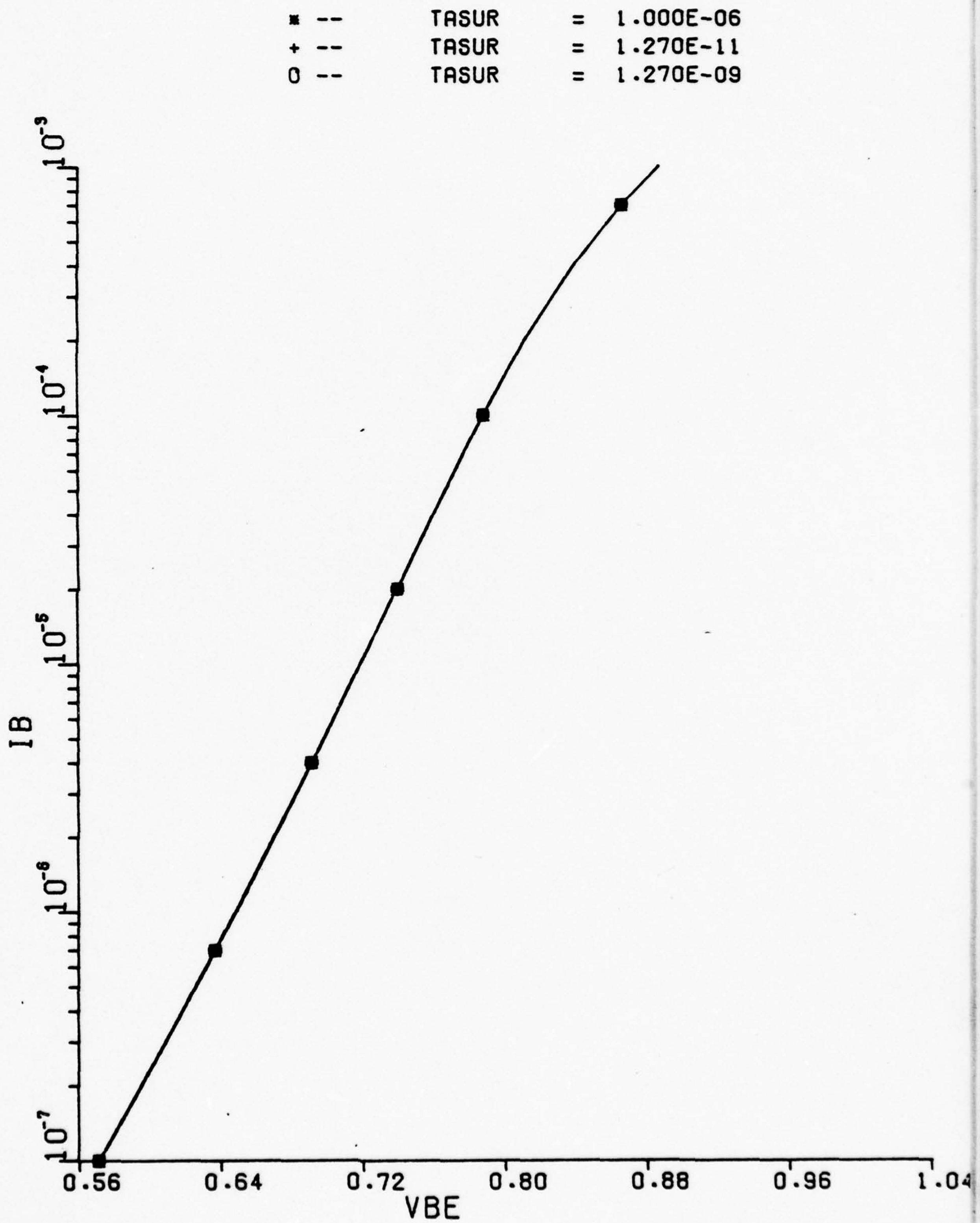
* -- VTS = 2.550E-02
+ -- VTS = 2.650E-02
0 -- VTS = 2.590E-02
IB
VBE
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04



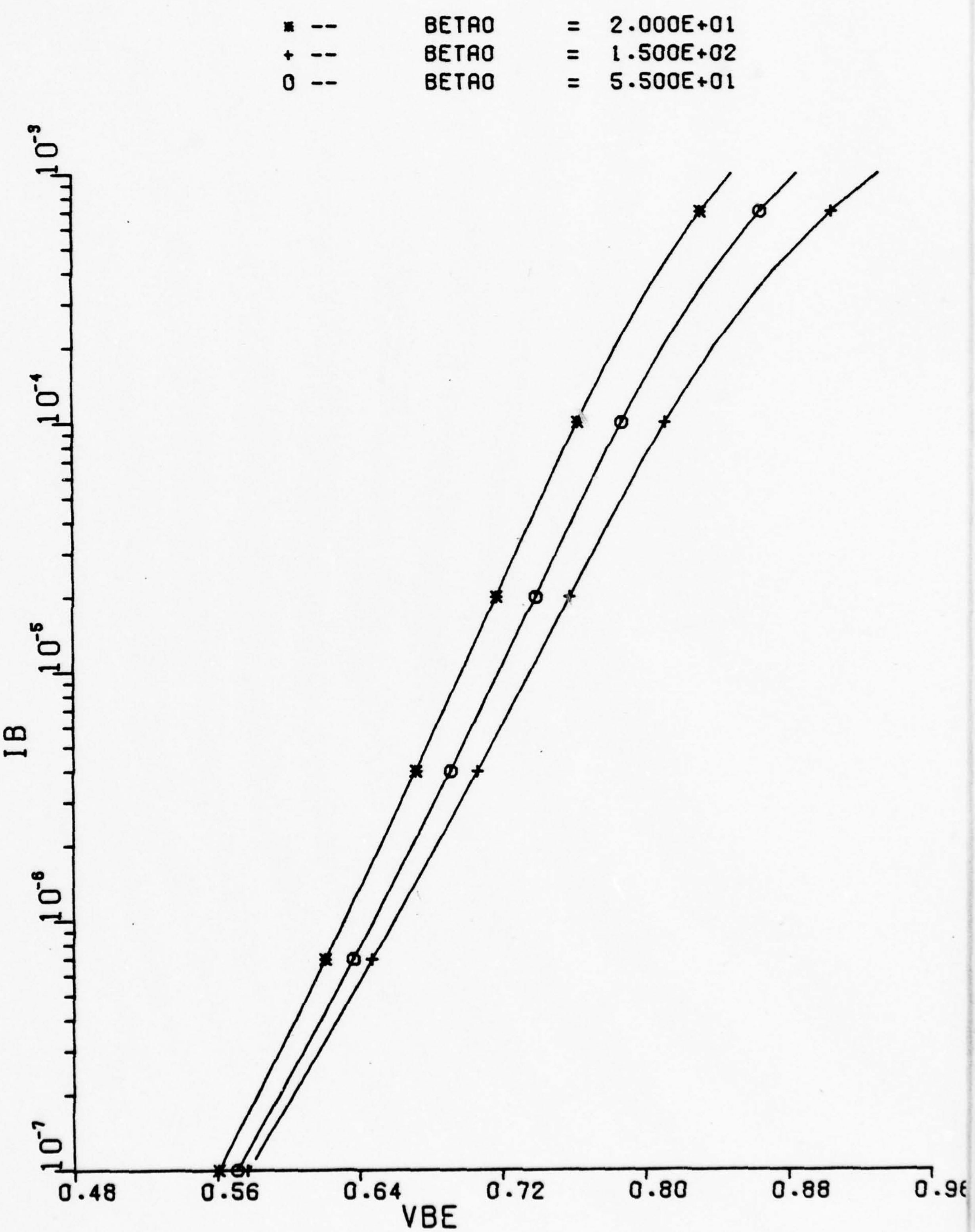
* -- QFN = 1.500E-18
+ -- QFN = 1.500E-14
O -- QFN = 1.500E-16
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE


* -- QRN = 1.500E-14
+ -- QRN = 1.500E-10
0 -- QRN = 1.500E-12
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96

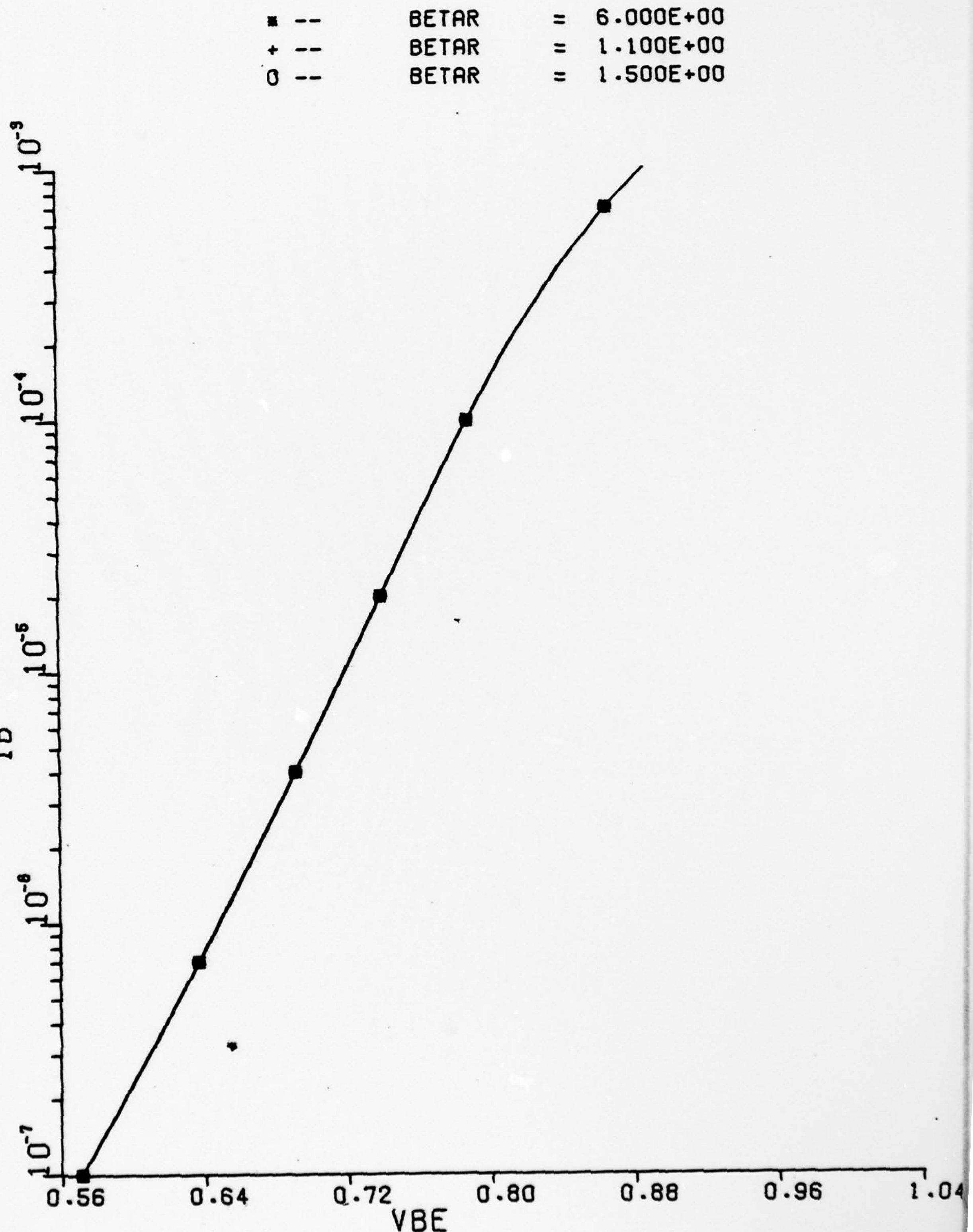

* -- TAUFO = 1.590E-09
+ -- TAUFO = 1.590E-08
0 -- TAUFO = 1.590E-10
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
IB
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



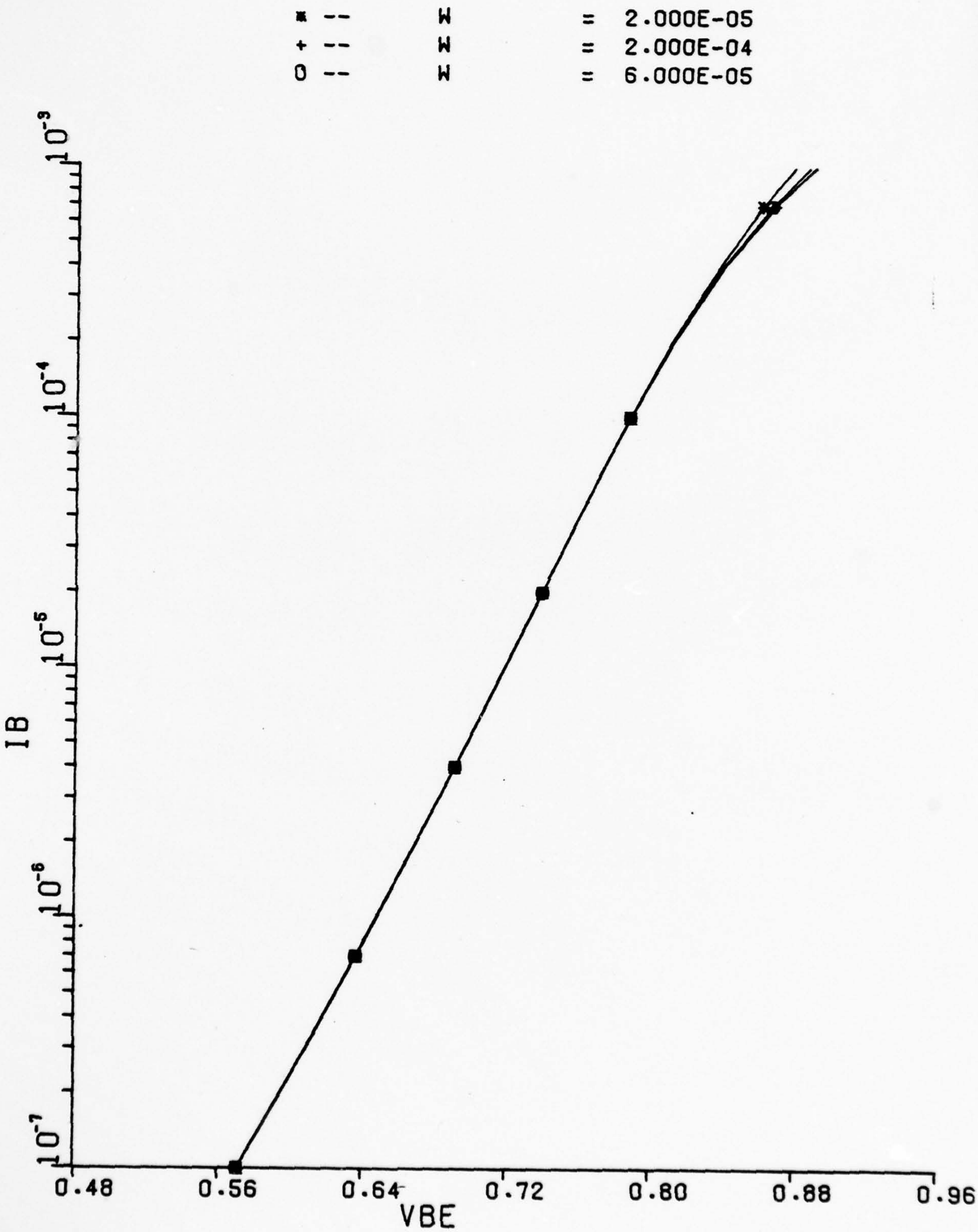
* -- TASUR = 1.000E-06
+ -- TASUR = 1.270E-11
0 -- TASUR = 1.270E-09
IB
10^-3
10^-4
10^-5
10^-6
10^-7
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



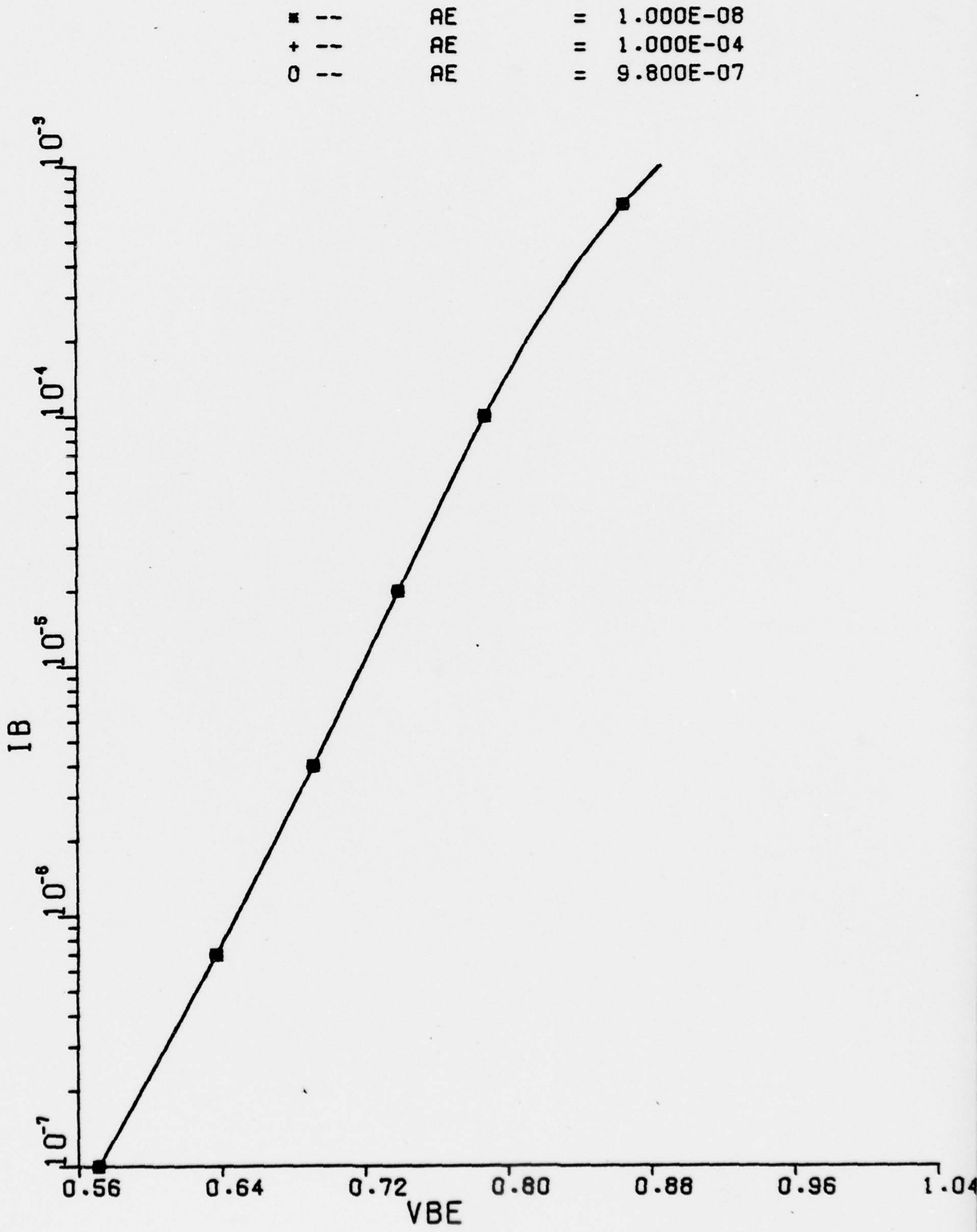
* -- BETAO = 2.000E+01
+ -- BETAO = 1.500E+02
O -- BETAO = 5.500E+01
IB
10^-3
10^-4
10^-5
10^-6
10^-7
0.48
0.56
0.64
0.72
0.80
0.88
0.96
VBE



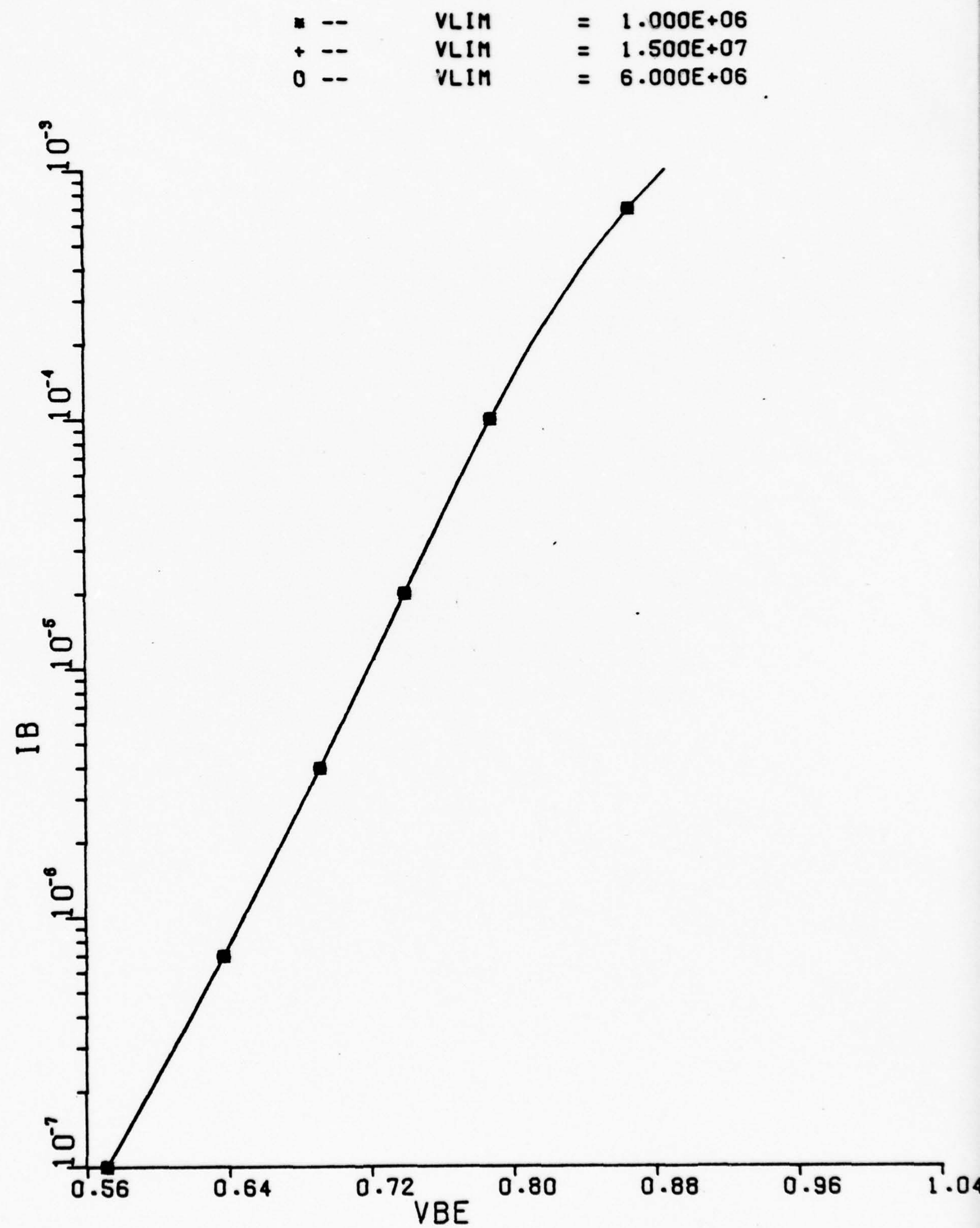
* -- BETAR = 6.000E+00
+ -- BETAR = 1.100E+00
O -- BETAR = 1.500E+00
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04



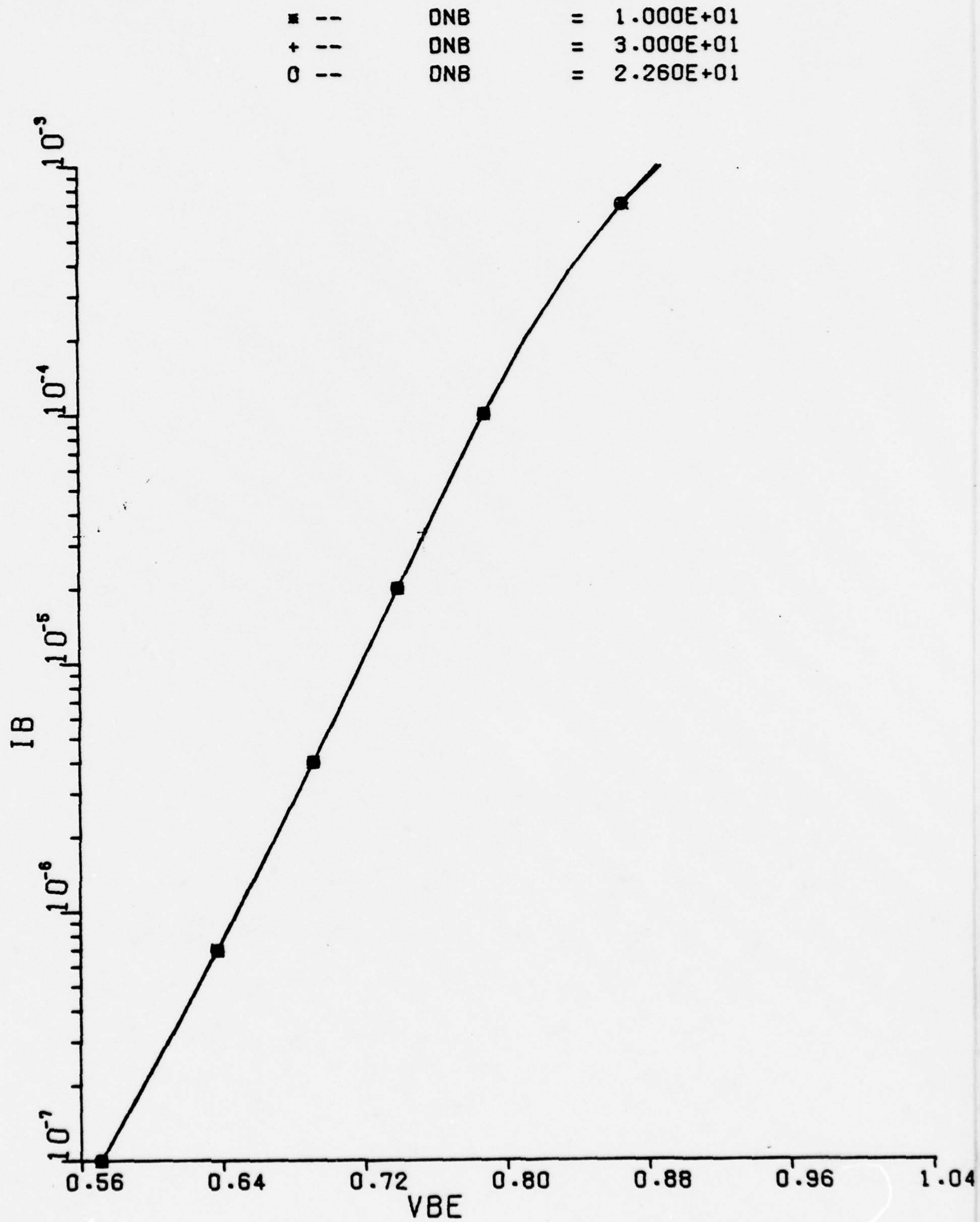
* -- W = 2.000E-05
+ -- W = 2.000E-04
O -- W = 6.000E-05
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.48
0.56
0.64
0.72
0.80
0.88
0.96
VBE



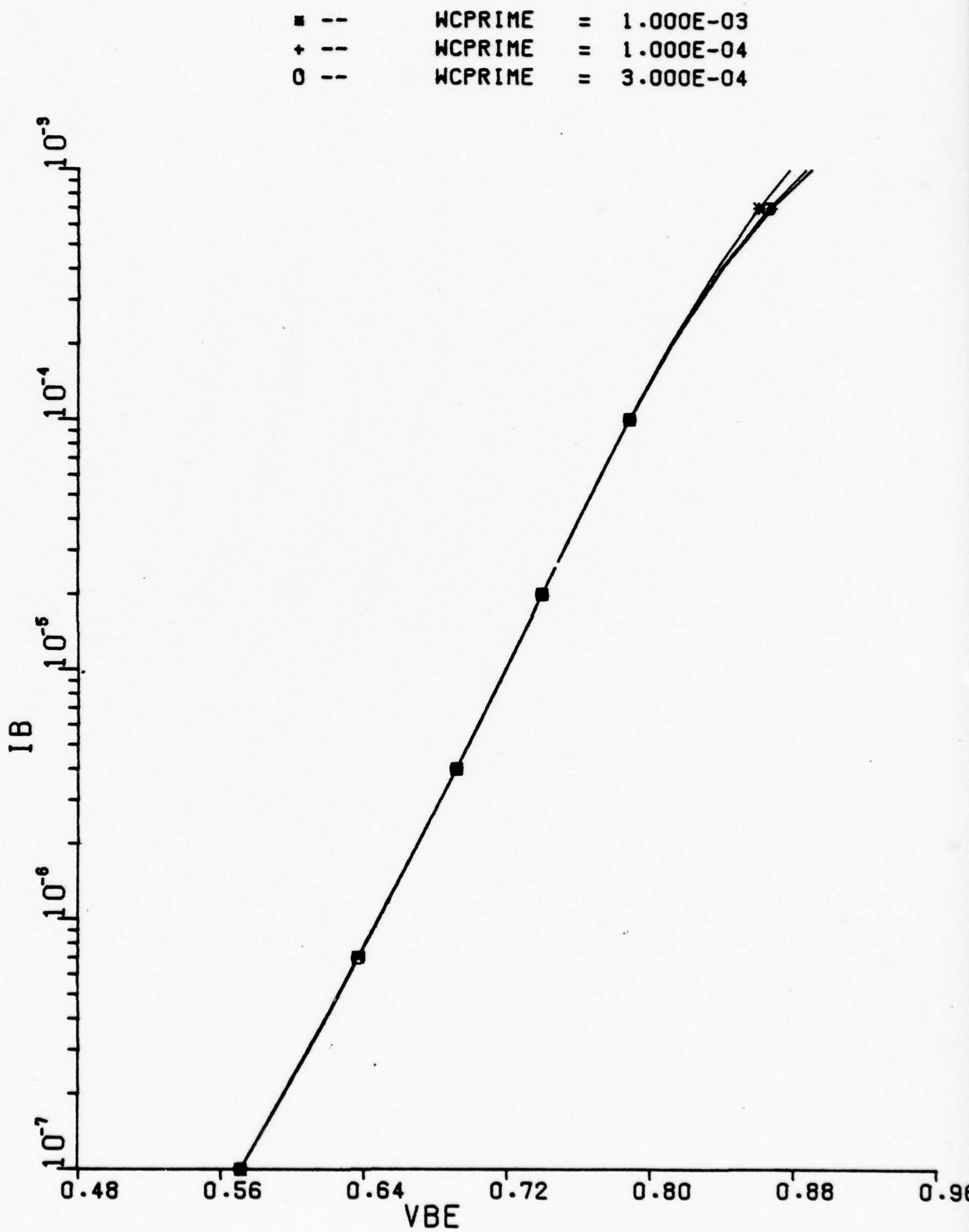
* -- AE = 1.000E-08
+ -- AE = 1.000E-04
0 -- AE = 9.800E-07
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

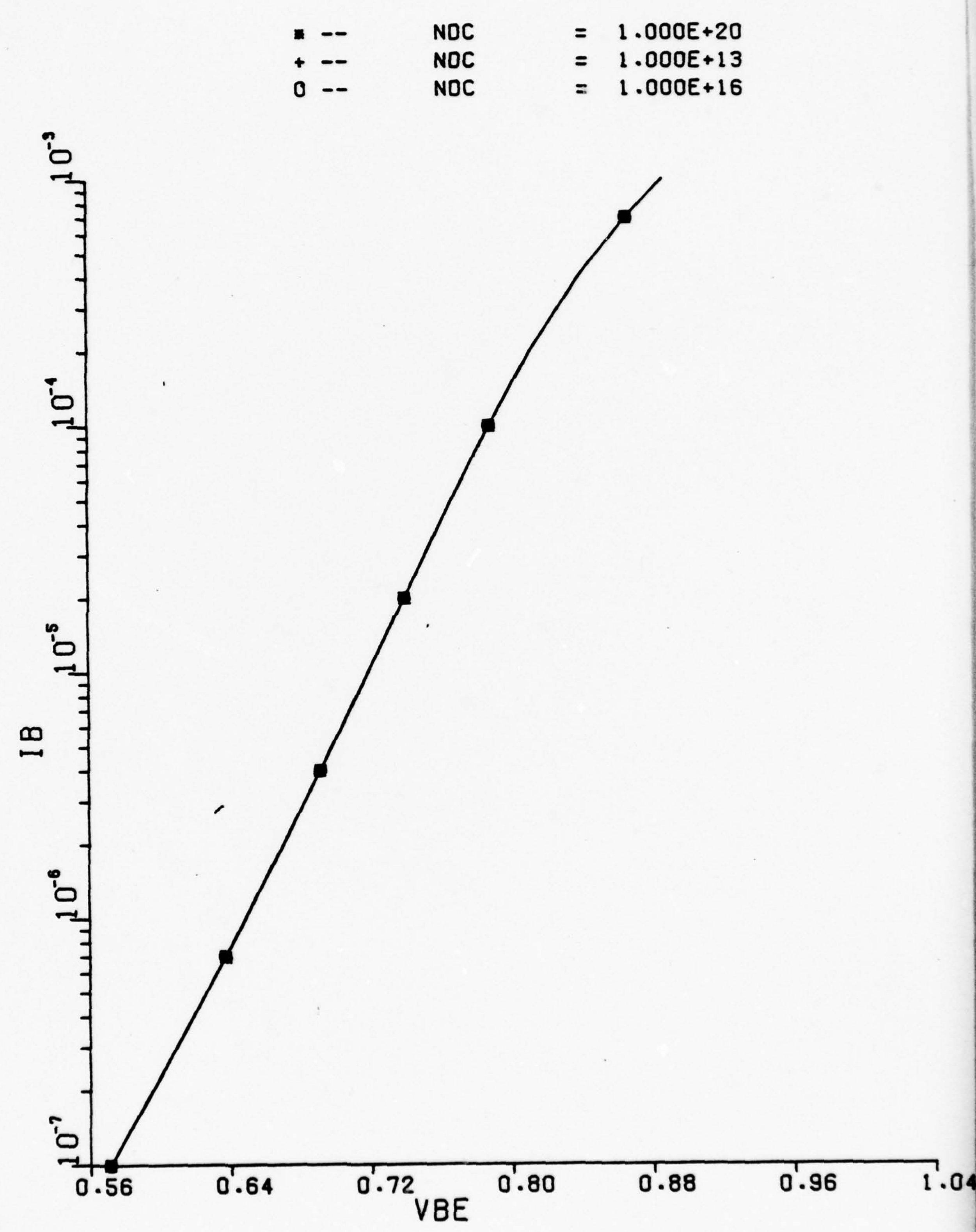


* -- VLIM = 1.000E+06
+ -- VLIM = 1.500E+07
0 -- VLIM = 6.000E+06
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

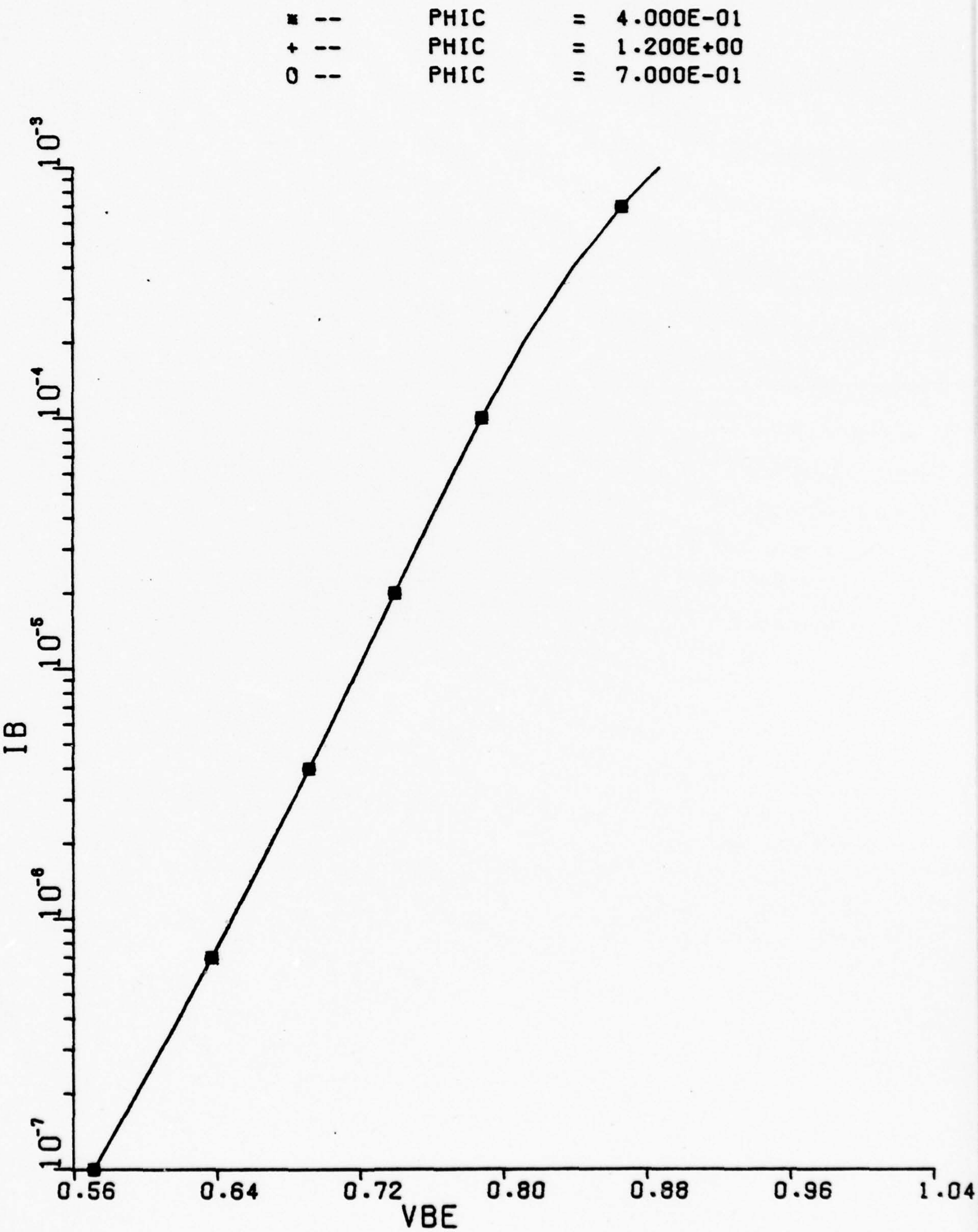


* -- DNB = 1.000E+01
+ -- DNB = 3.000E+01
0 -- DNB = 2.260E+01
IB
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

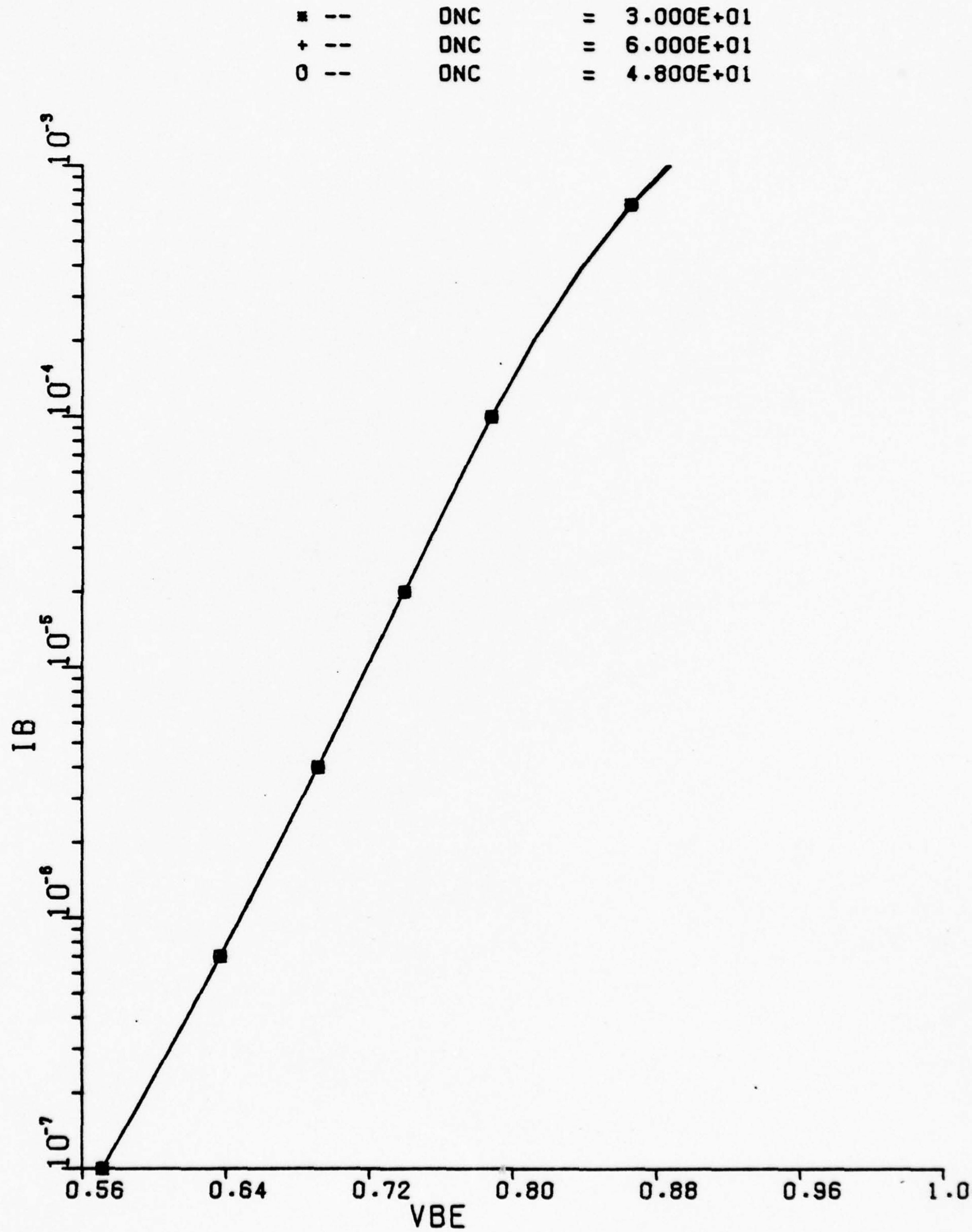

■ -- WCPRIME = 1.000E-03
+ -- WCPRIME = 1.000E-04
O -- WCPRIME = 3.000E-04
10^-3
10^-4
10^-5
10^-6
10^-7
IB
0.48
0.56
0.64
0.72
0.80
0.88
0.96
VBE



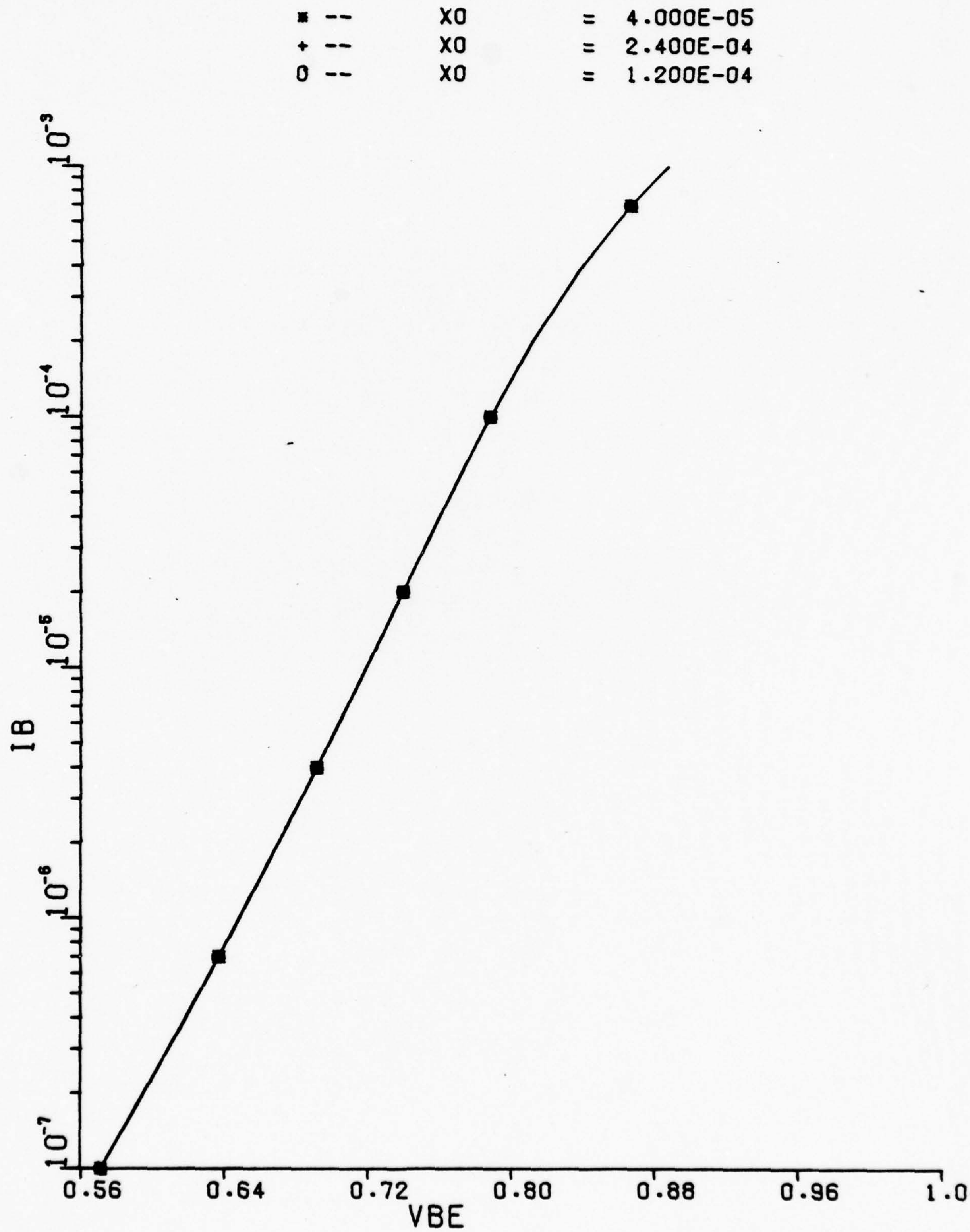
■ -- NDC = 1.000E+20
+ -- NDC = 1.000E+13
O -- NDC = 1.000E+16
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



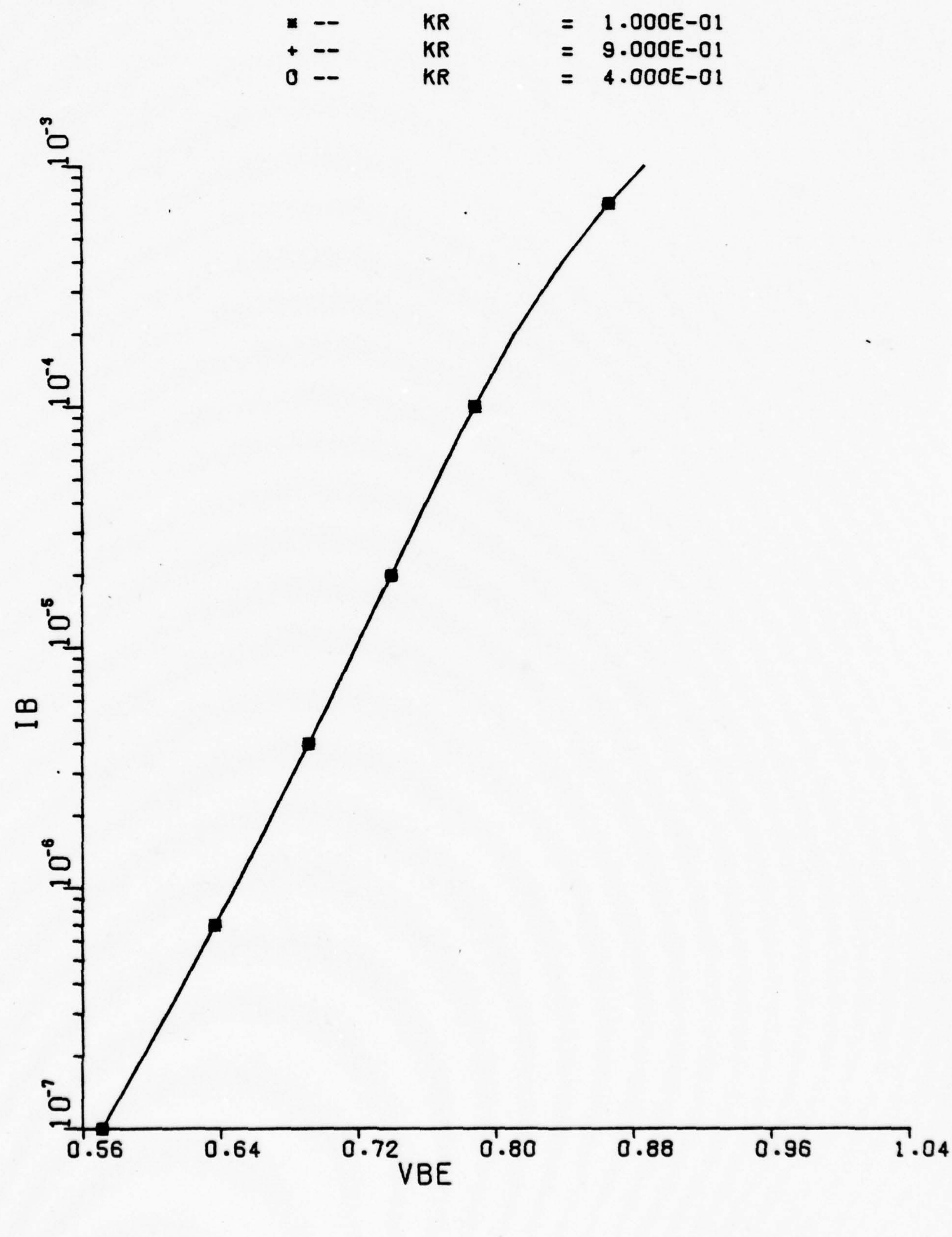
* -- PHIC = 4.000E-01
+ -- PHIC = 1.200E+00
0 -- PHIC = 7.000E-01
IB
10^-3
10^-4
10^-5
10^-6
10^-7
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



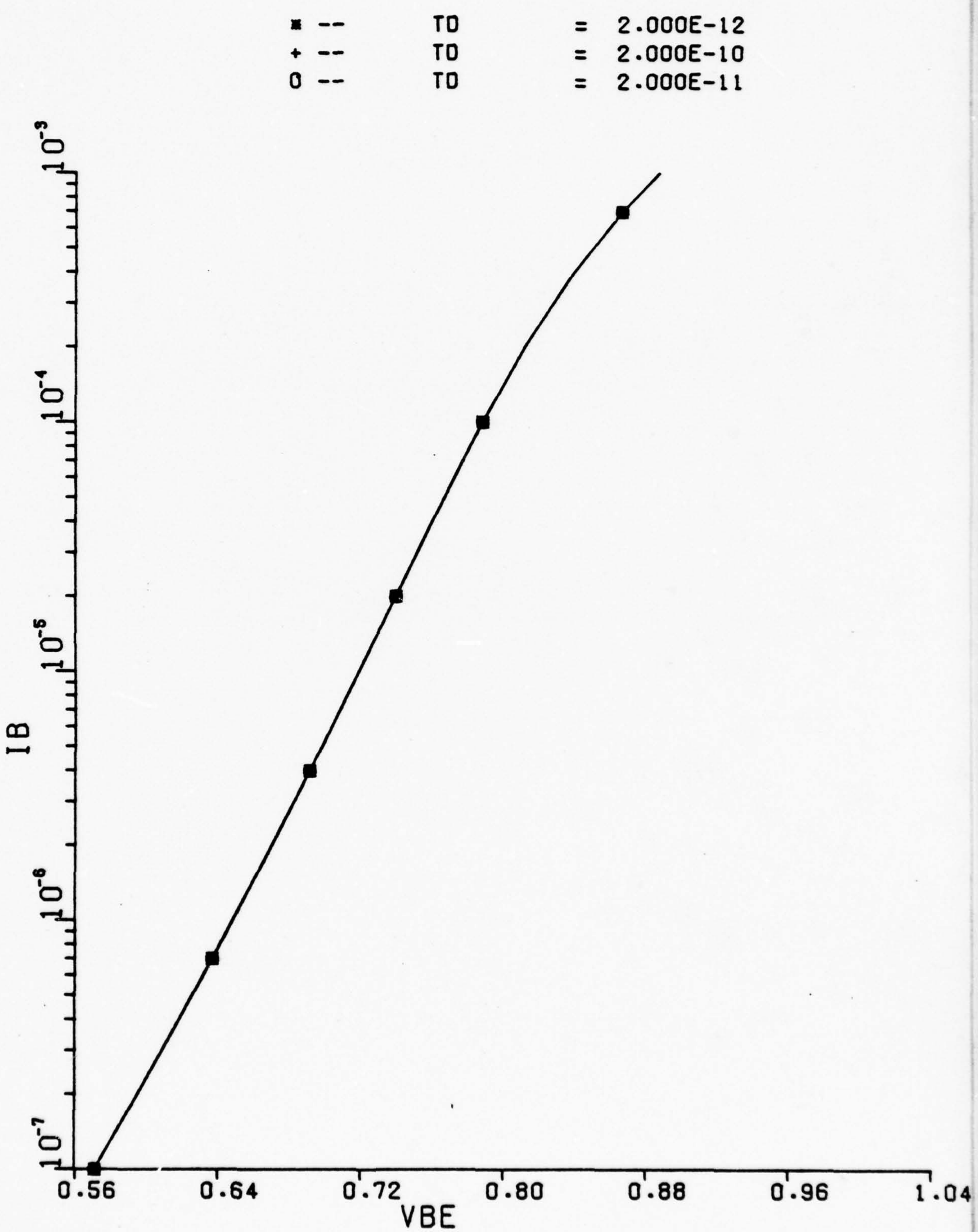
* -- DNC = 3.000E+01
+ -- DNC = 6.000E+01
0 -- DNC = 4.800E+01
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



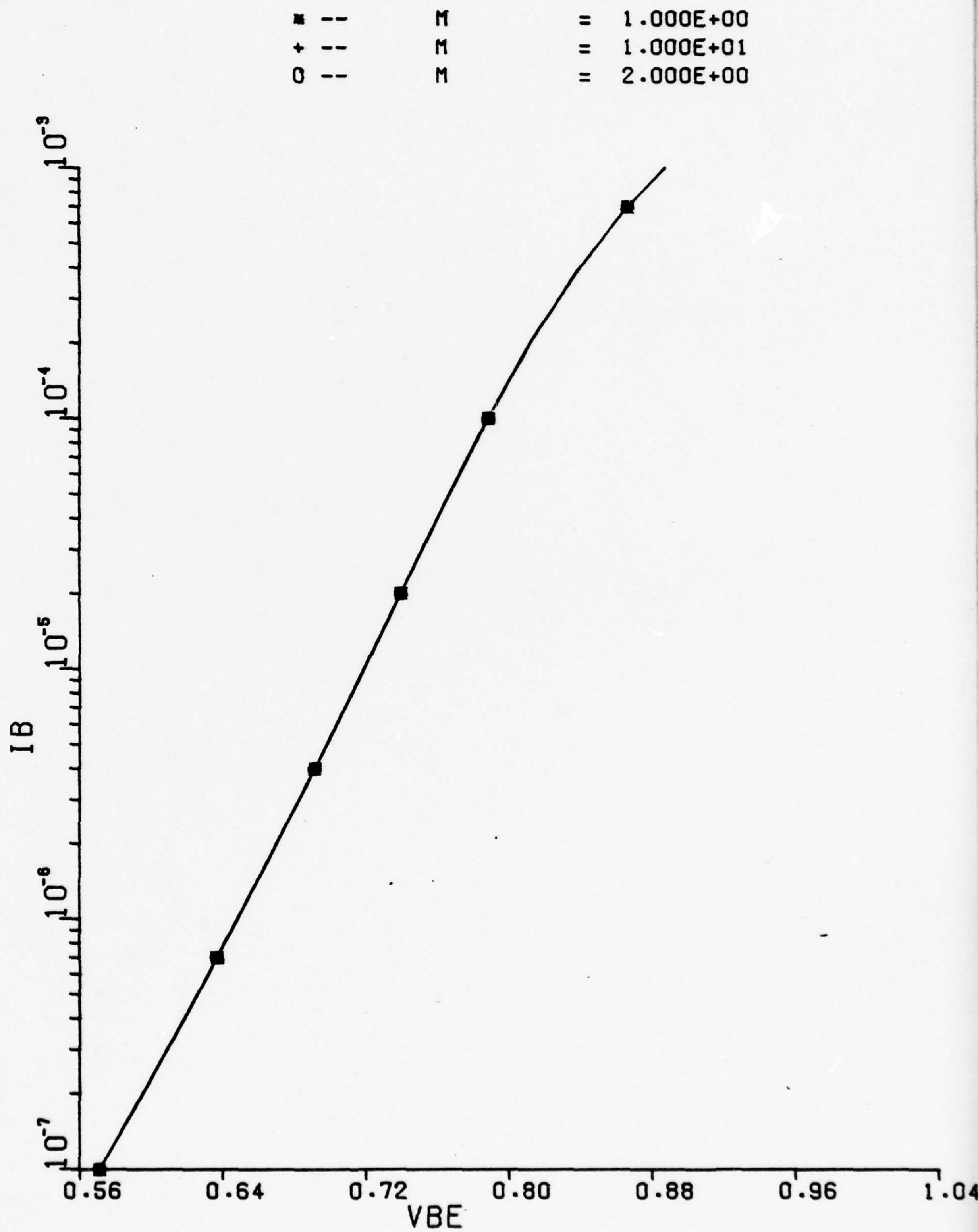
* -- XO = 4.000E-05
+ -- XO = 2.400E-04
0 -- XO = 1.200E-04
IB
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



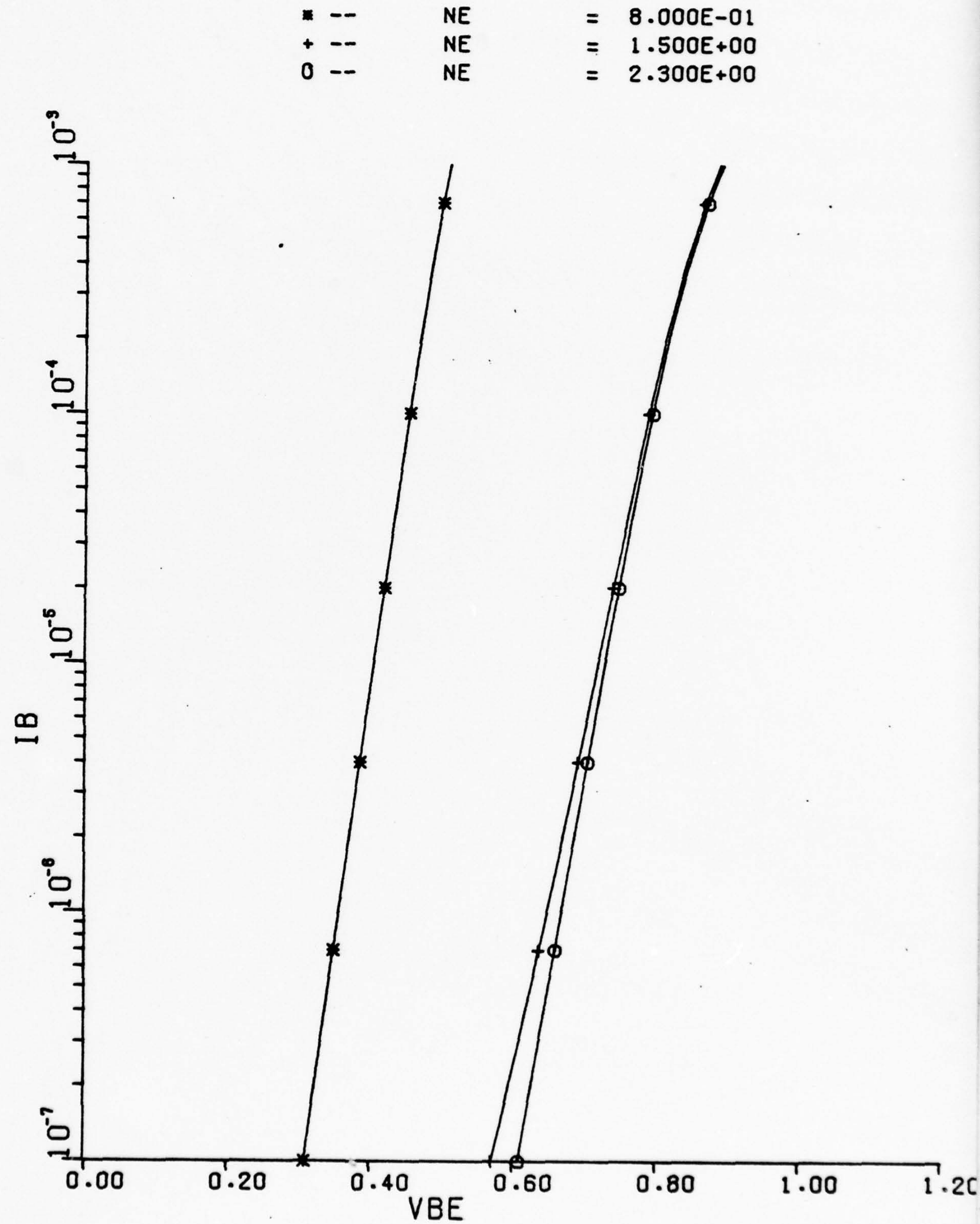
■ -- KR = 1.000E-01
+ -- KR = 9.000E-01
O -- KR = 4.000E-01
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



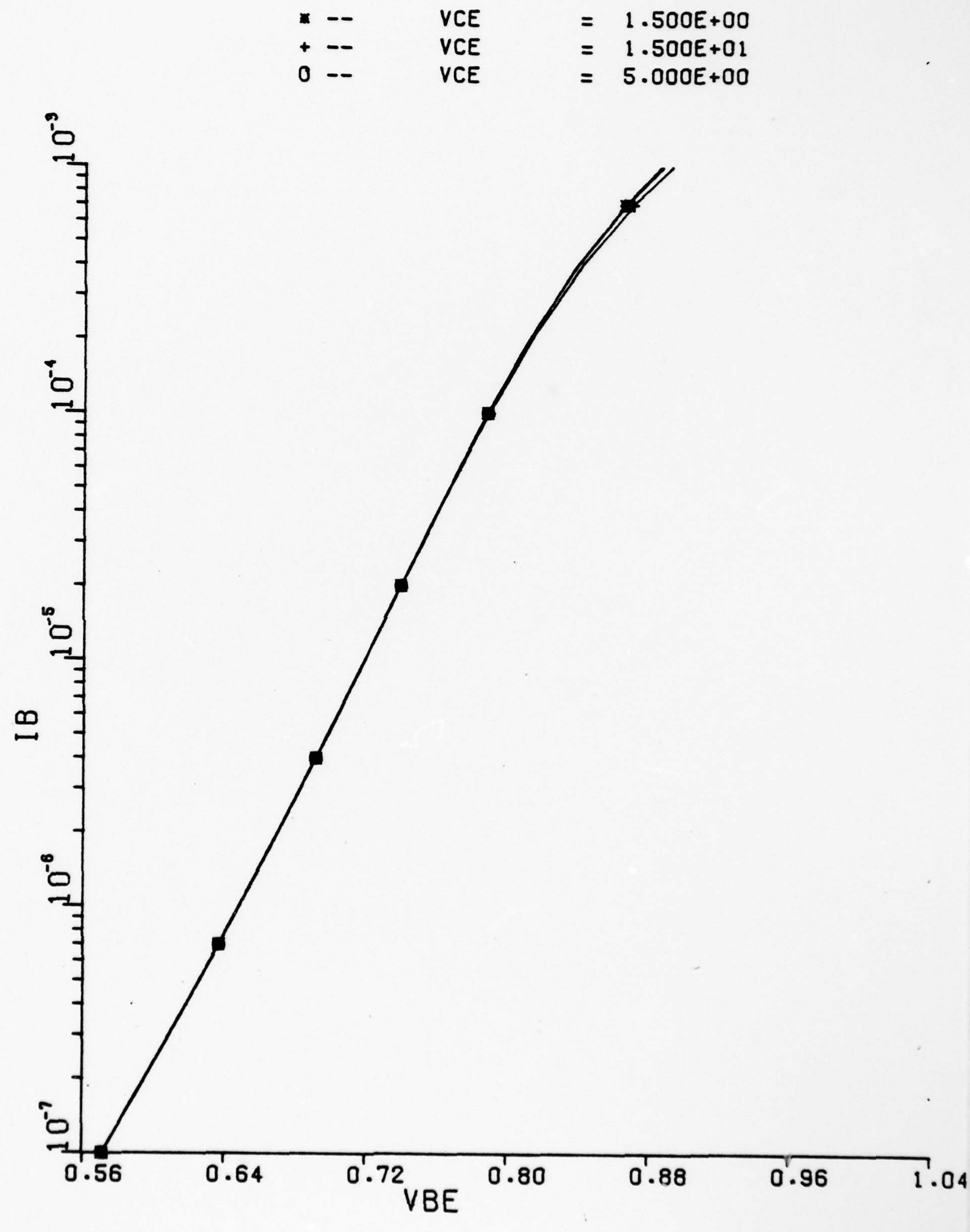
* -- TD = 2.000E-12
+ -- TD = 2.000E-10
0 -- TD = 2.000E-11
IB
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04



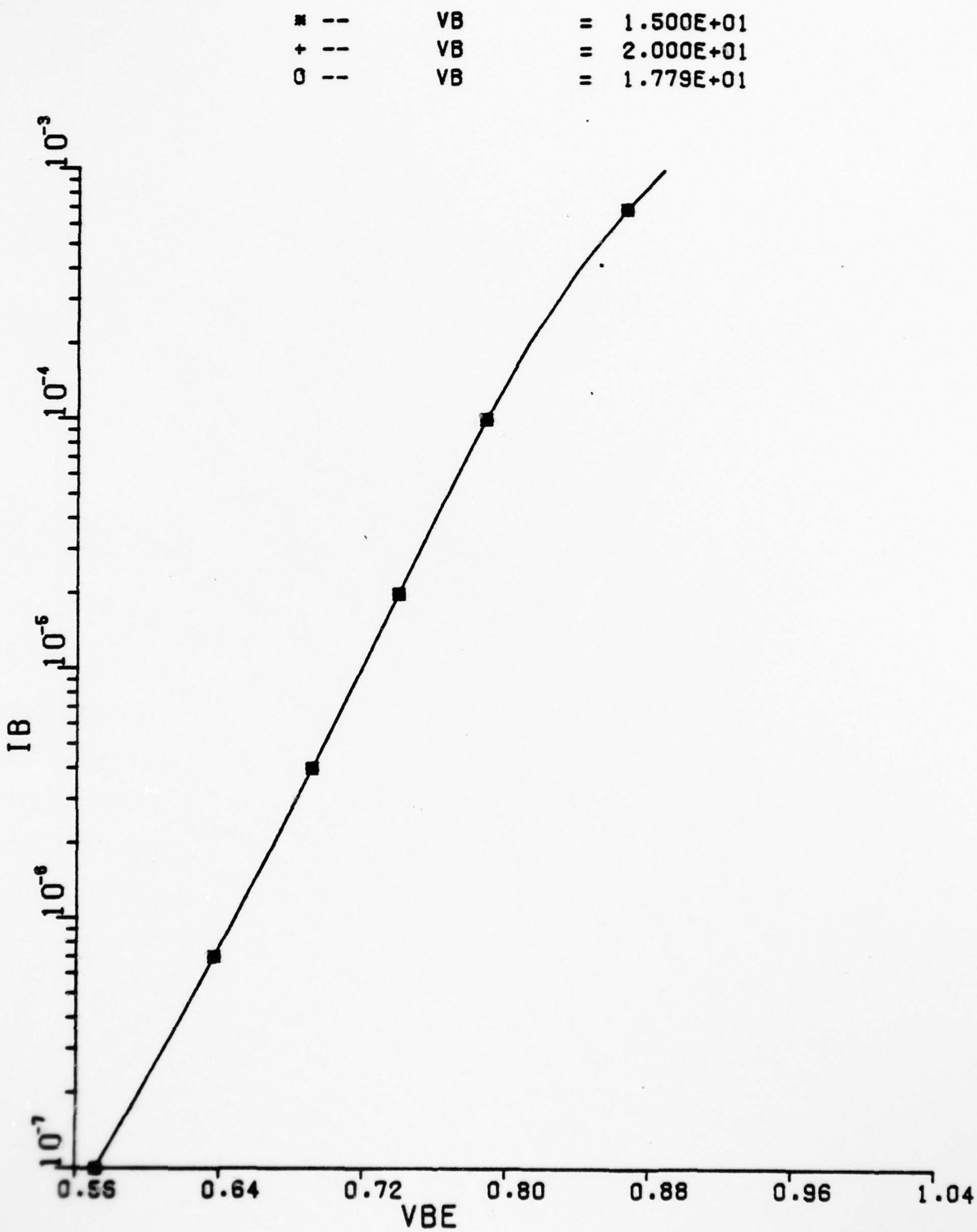
* -- M = 1.000E+00
+ -- M = 1.000E+01
0 -- M = 2.000E+00
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04



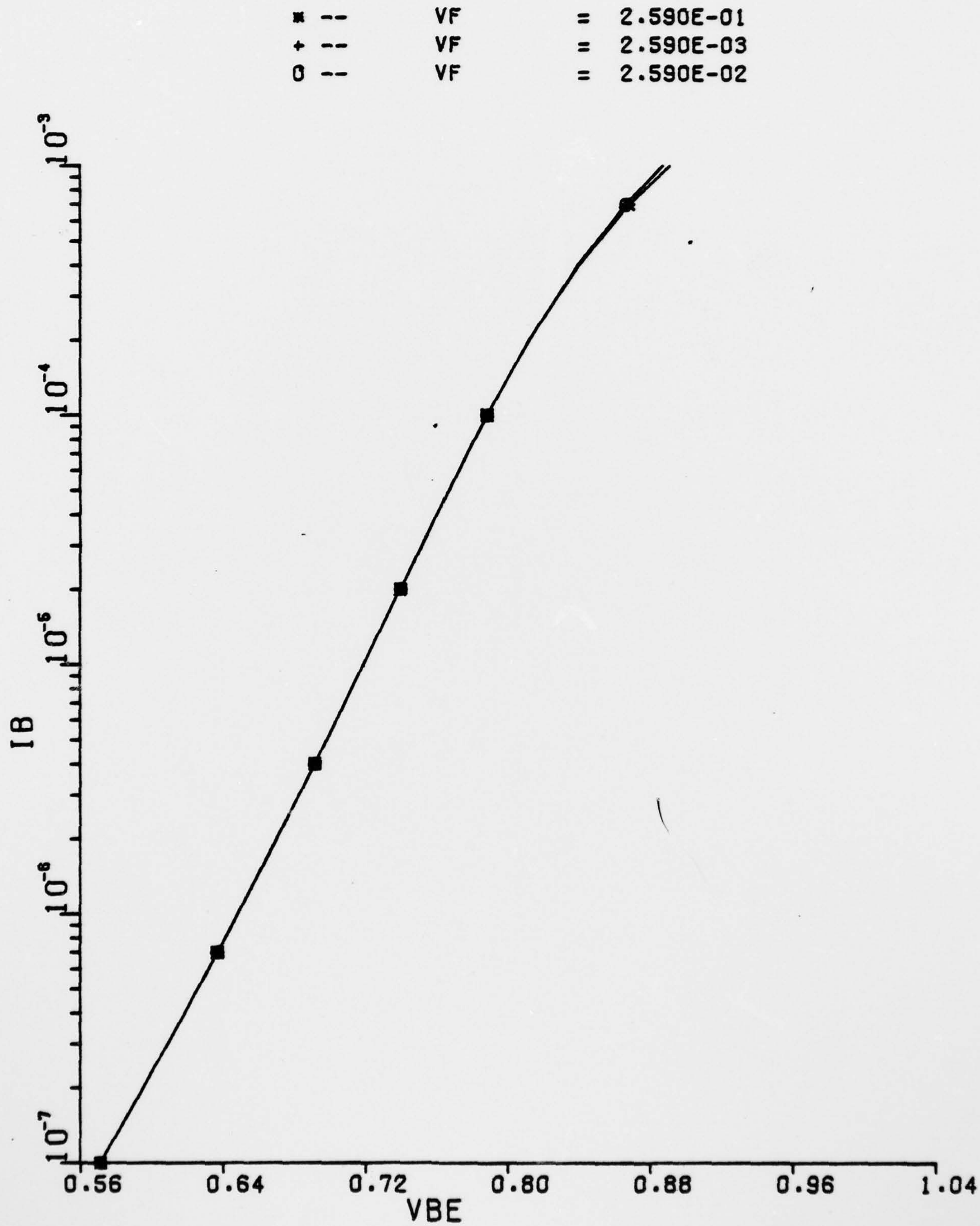
* -- NE = 8.000E-01
+ -- NE = 1.500E+00
O -- NE = 2.300E+00
IB
VBE
0.00
0.20
0.40
0.60
0.80
1.00
1.20



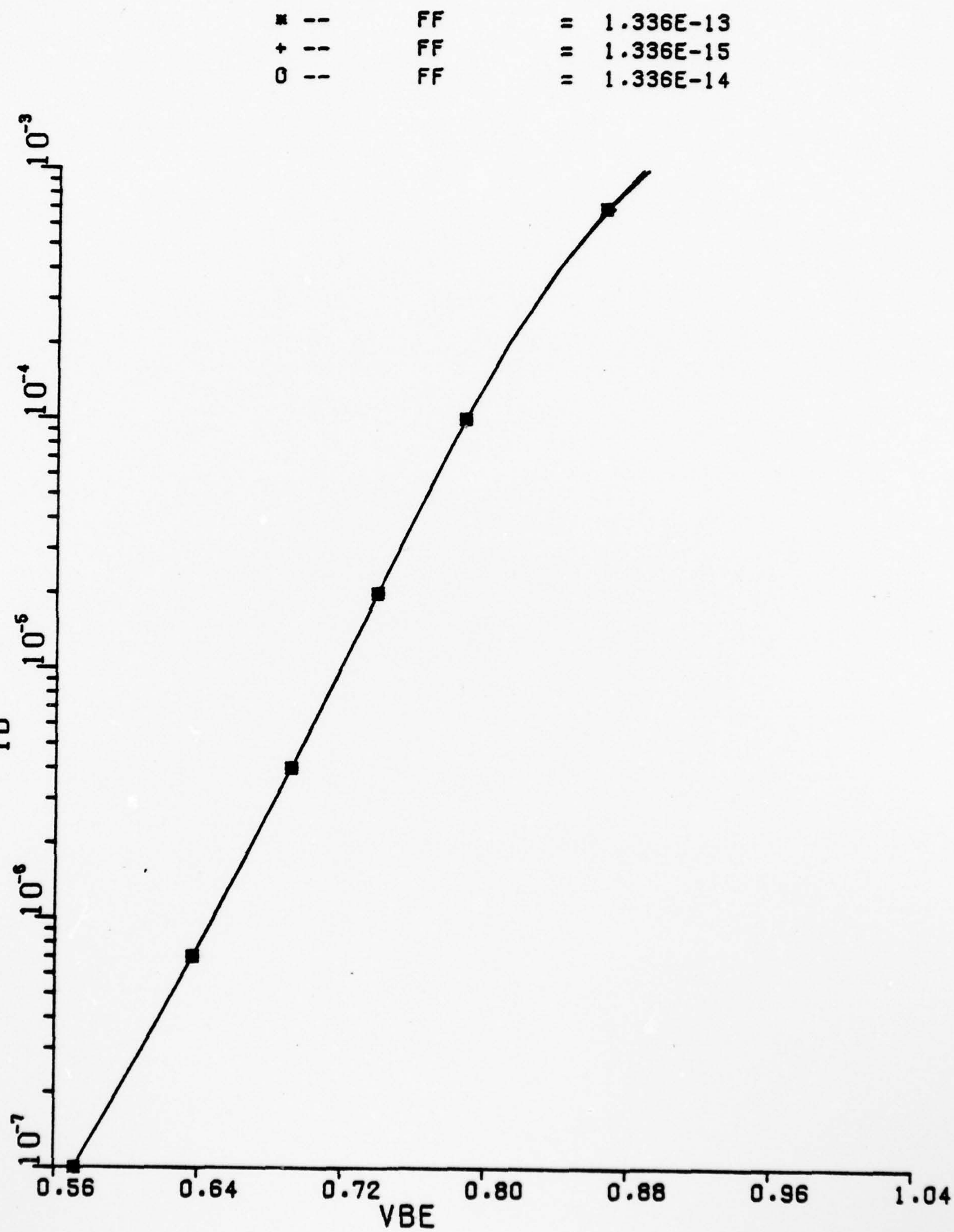
* -- VCE = 1.500E+00
+ -- VCE = 1.500E+01
0 -- VCE = 5.000E+00
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04



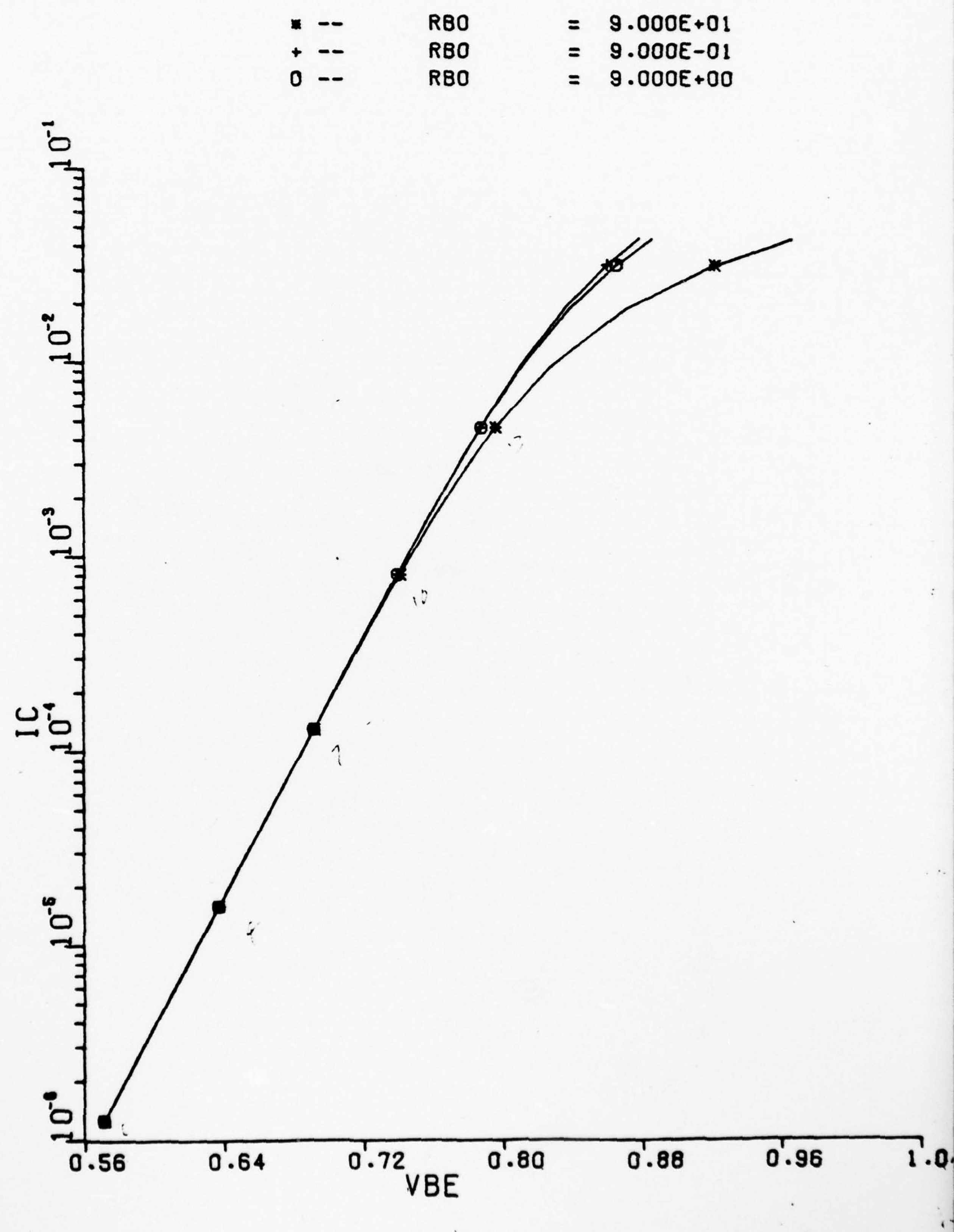
* -- VB = 1.500E+01
+ -- VB = 2.000E+01
0 -- VB = 1.779E+01
IB
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

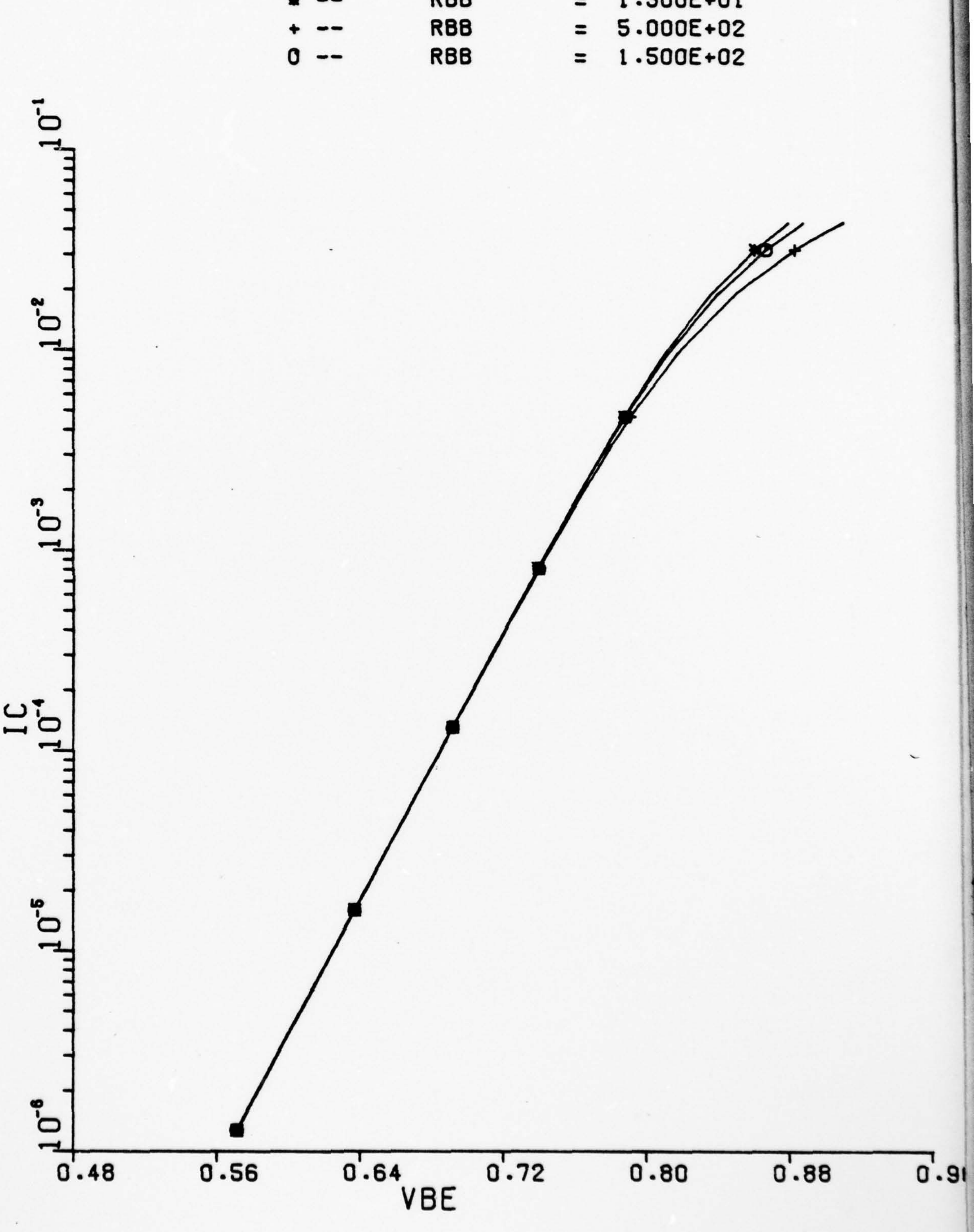


* -- VF = 2.590E-01
+ -- VF = 2.590E-03
0 -- VF = 2.590E-02
IB
$10^{-3}$
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-7}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

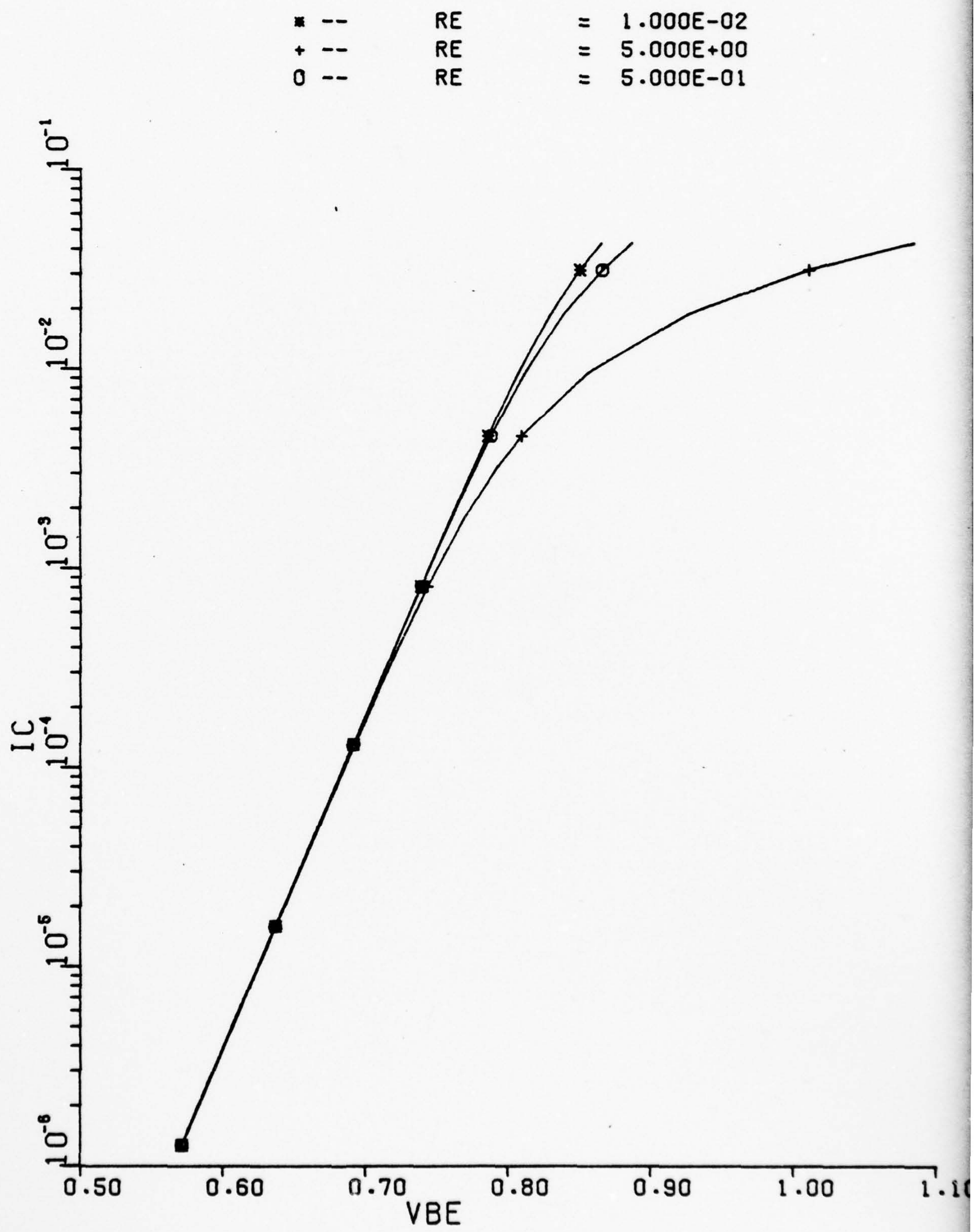

* -- FF = 1.336E-13
+ -- FF = 1.336E-15
O -- FF = 1.336E-14
IB
10^-3
10^-4
10^-5
10^-6
10^-7
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

B.2 $I_c$ vs. $V_{BE}$ Curves

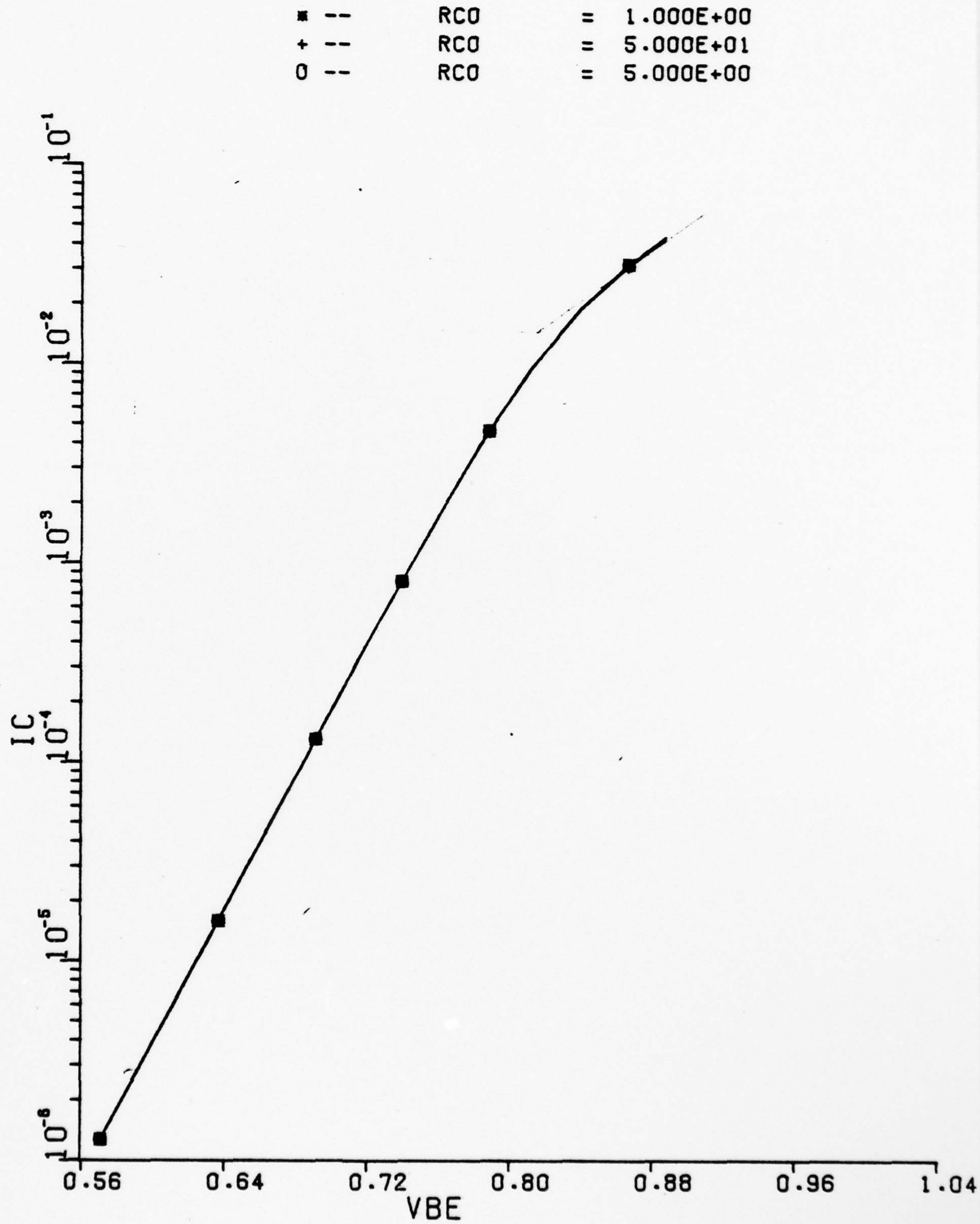

* -- RBO = 9.000E+01
+ -- RBO = 9.000E-01
0 -- RBO = 9.000E+00
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.0
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁶
10⁻⁸



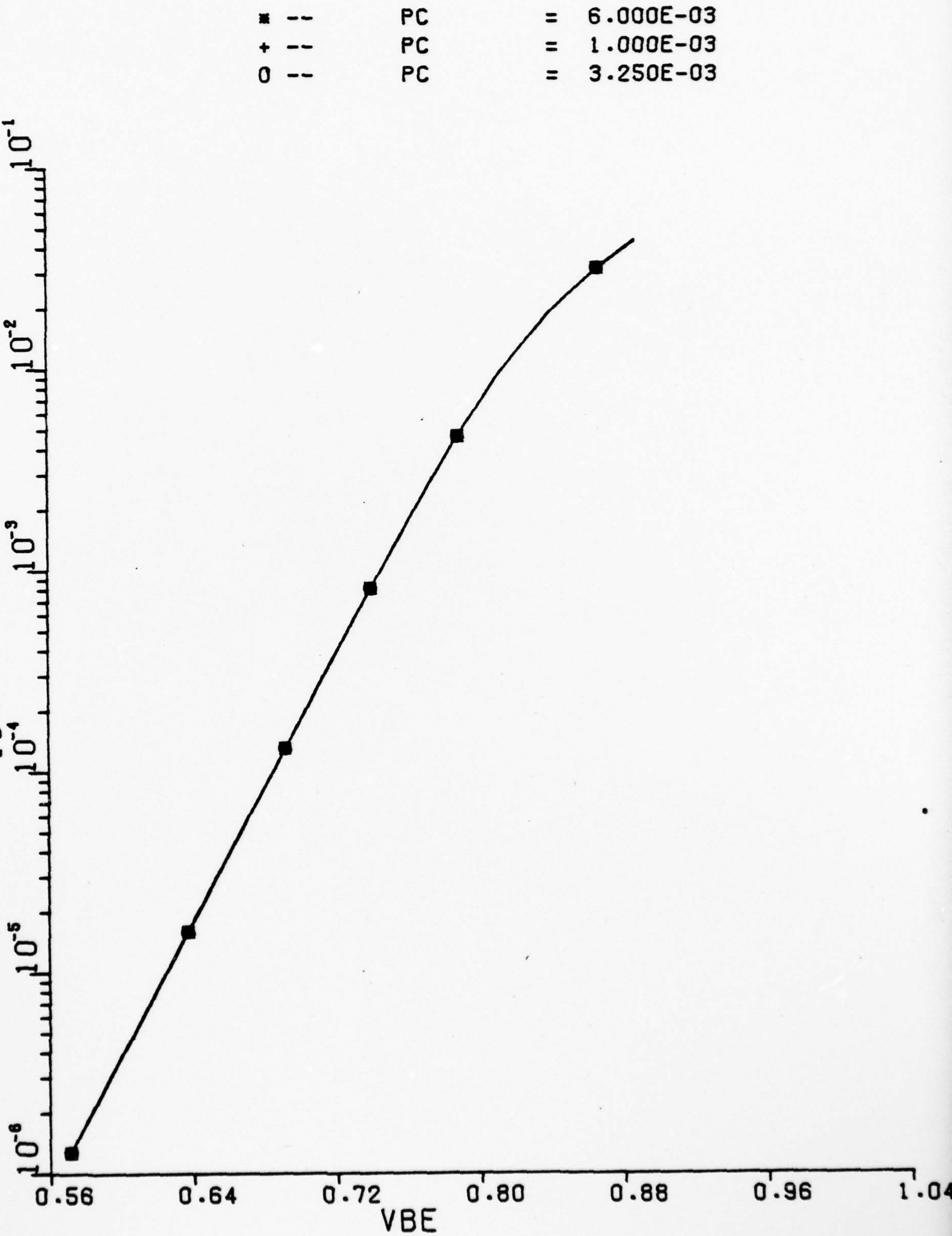
* -- RBB = 1.500E+01
+ -- RBB = 5.000E+02
O -- RBB = 1.500E+02
IC
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.48
0.56
0.64
0.72
0.80
0.88
VBE



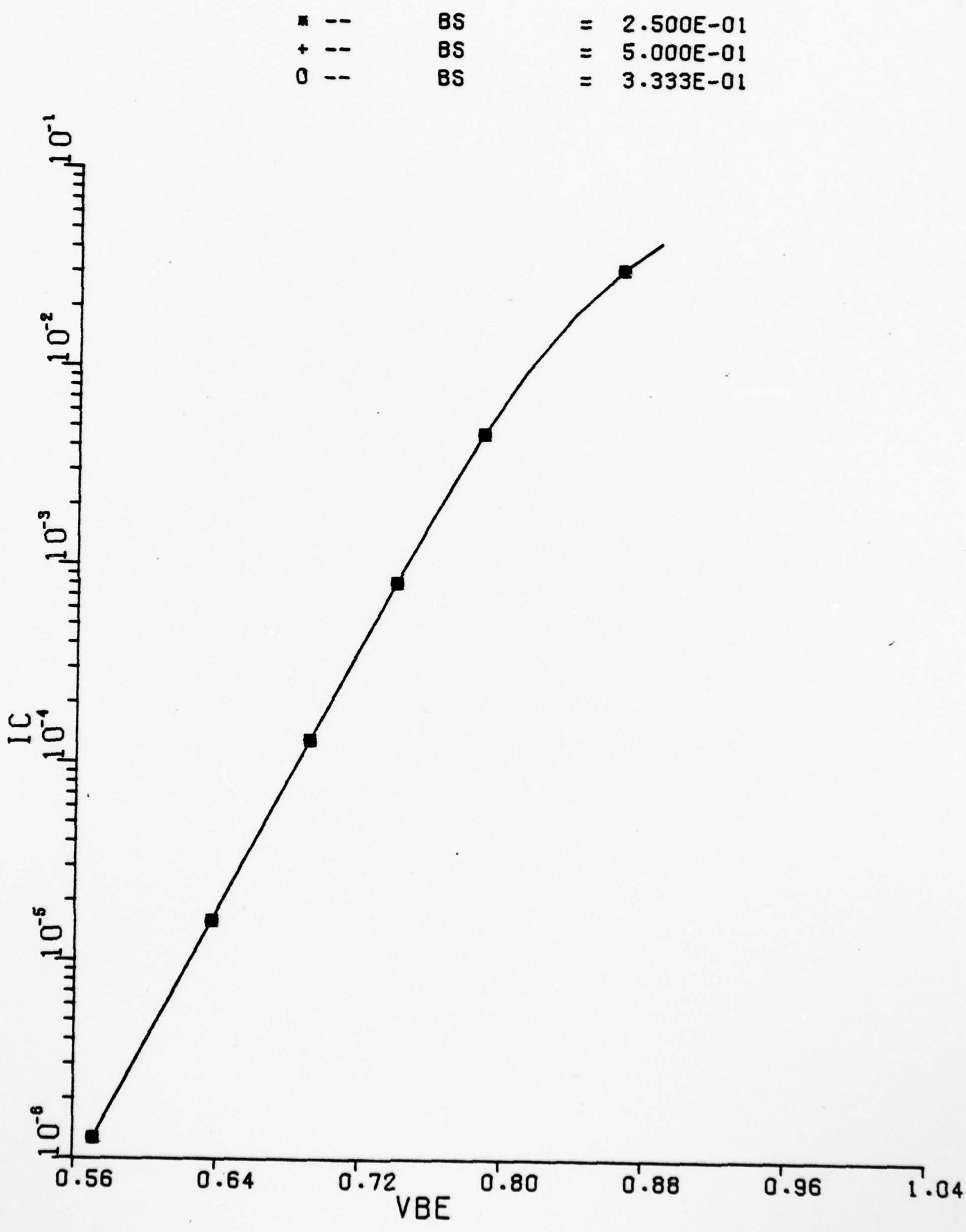
* -- RE = 1.000E-02
+ -- RE = 5.000E+00
O -- RE = 5.000E-01
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.50
0.60
0.70
0.80
0.90
1.00
1.10
VBE

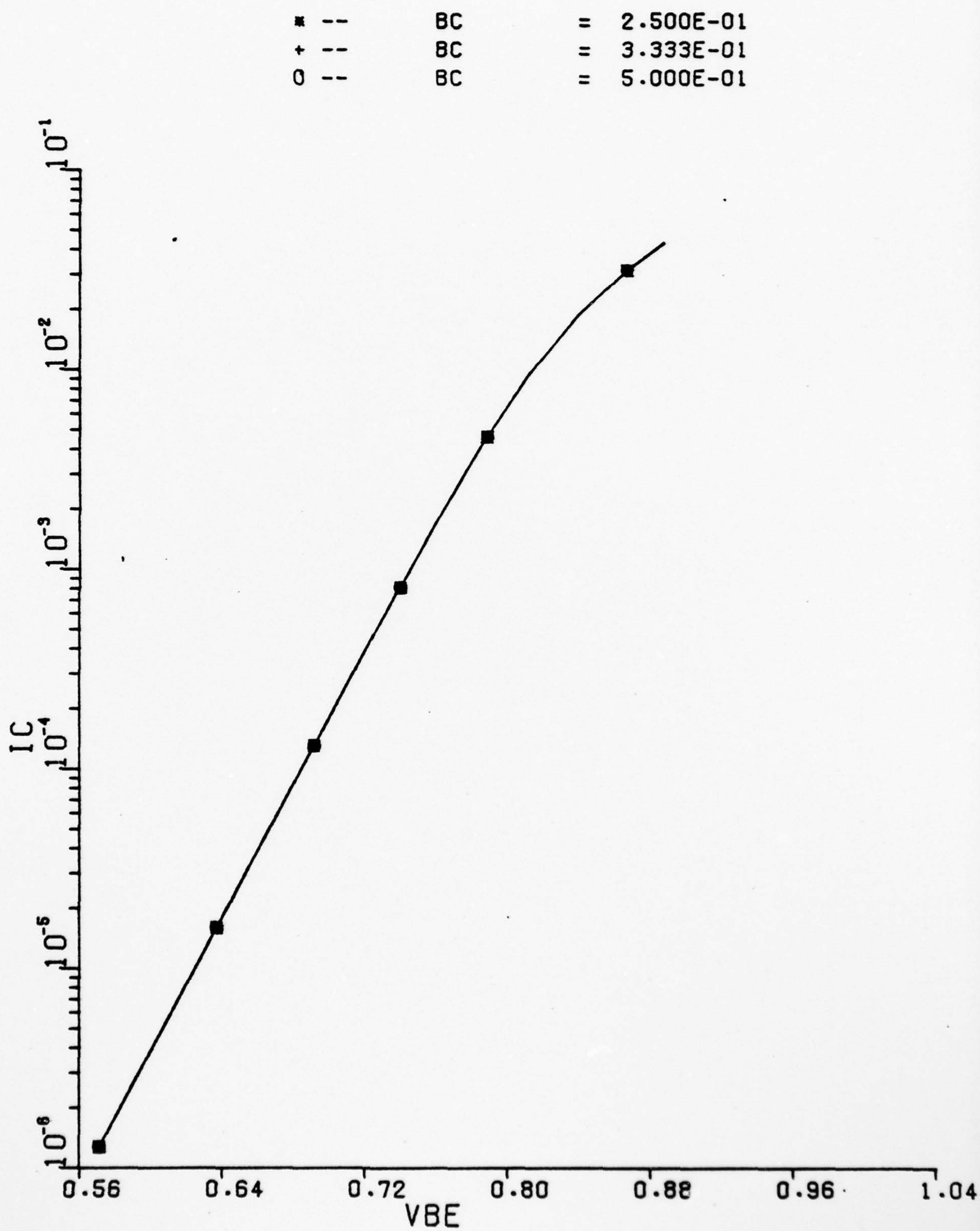


* -- RCO = 1.000E+00
+ -- RCO = 5.000E+01
O -- RCO = 5.000E+00
IC
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

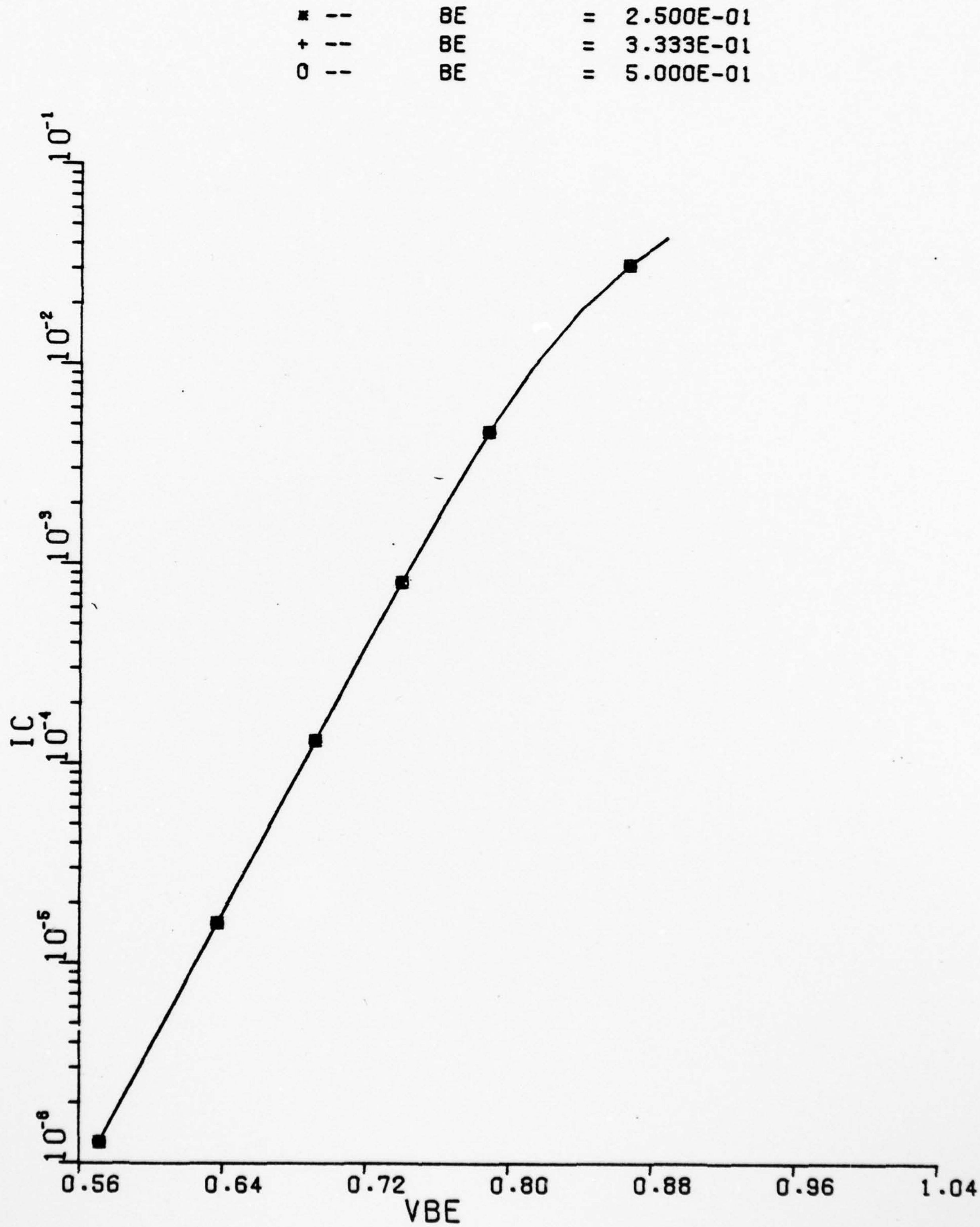


* -- PC = 6.000E-03
+ -- PC = 1.000E-03
0 -- PC = 3.250E-03
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
IC
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

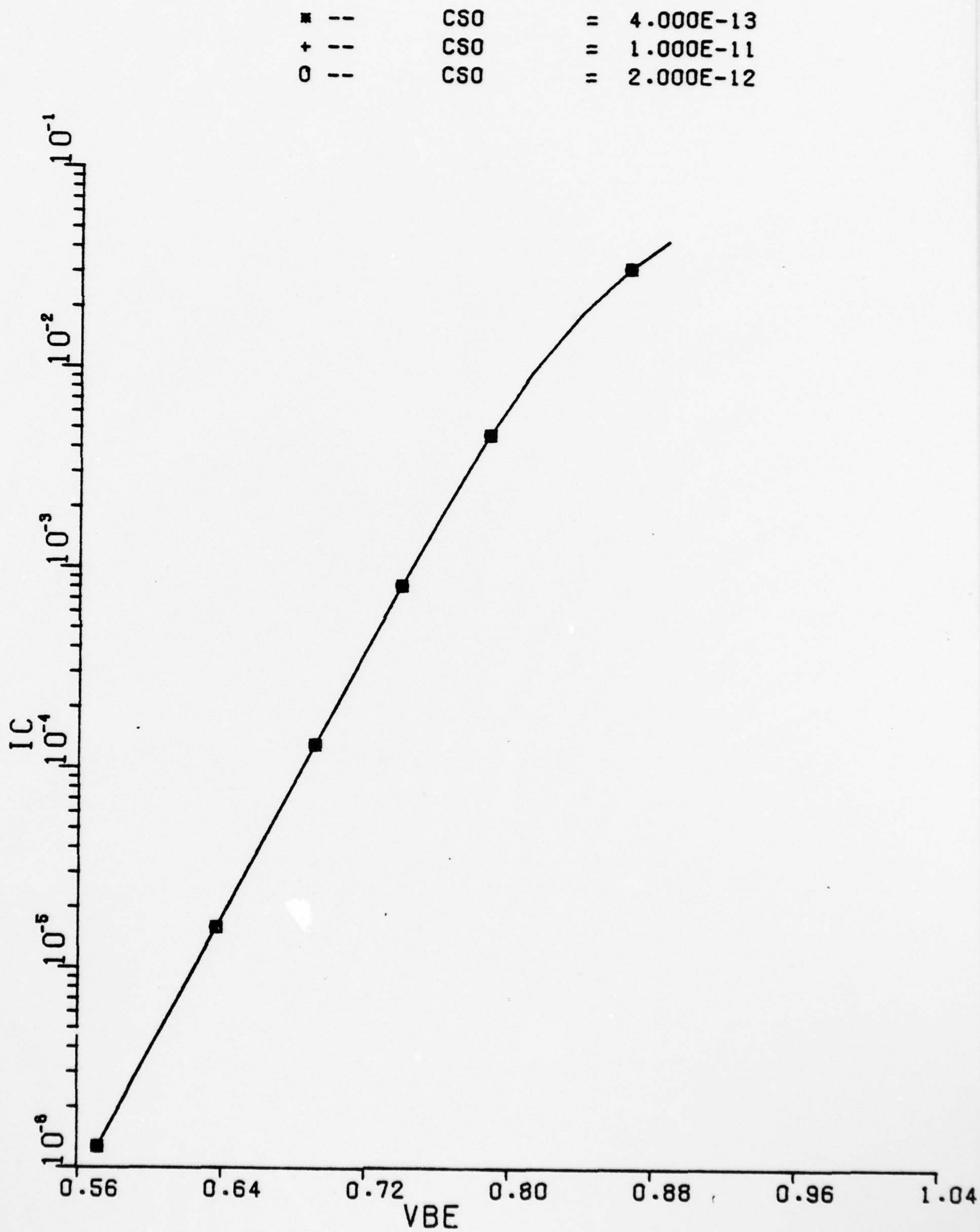

* -- BS = 2.500E-01
+ -- BS = 5.000E-01
0 -- BS = 3.333E-01
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04



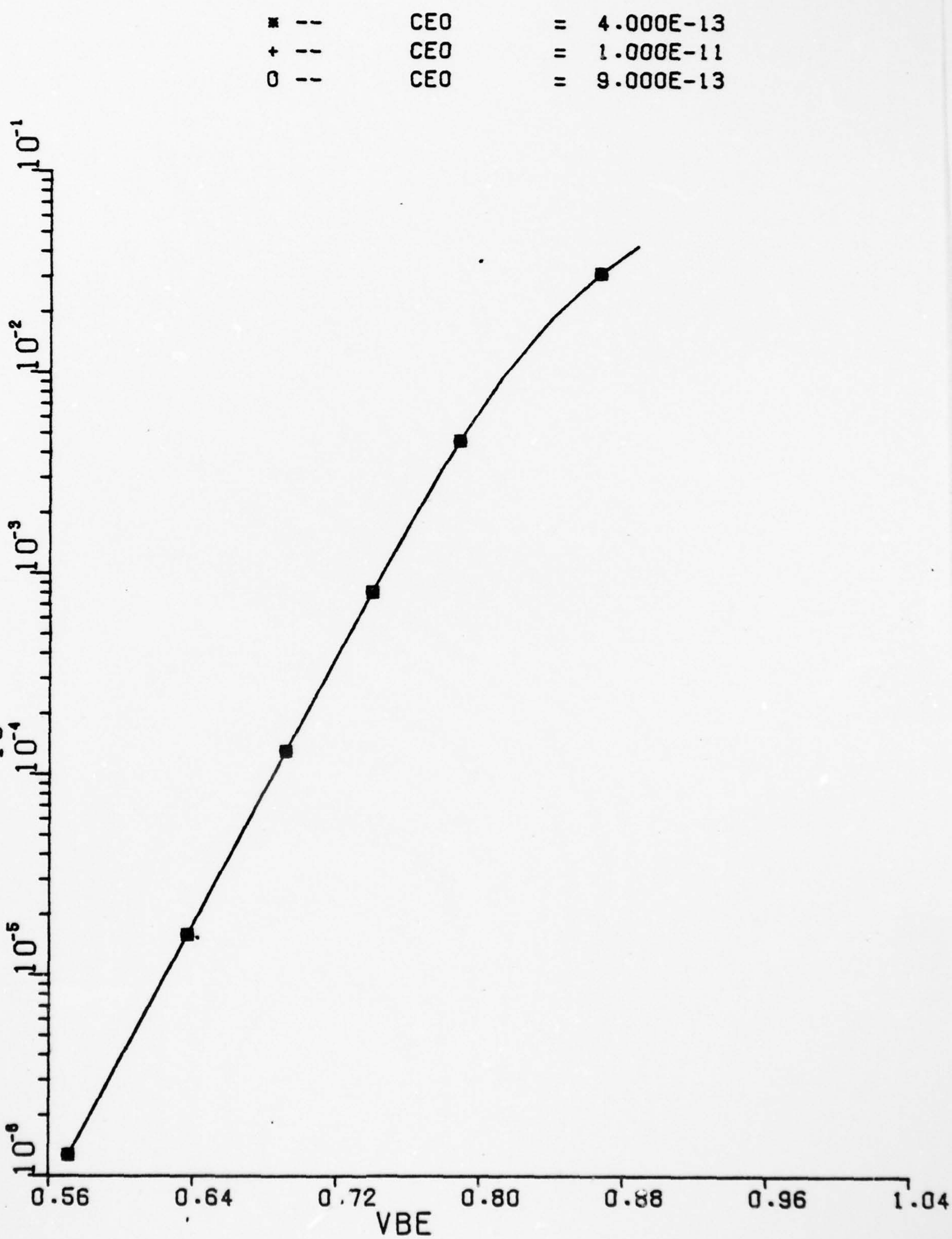
* -- BC = 2.500E-01
+ -- BC = 3.333E-01
0 -- BC = 5.000E-01
IC
VBE
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04



* -- BE = 2.500E-01
+ -- BE = 3.333E-01
0 -- BE = 5.000E-01
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04



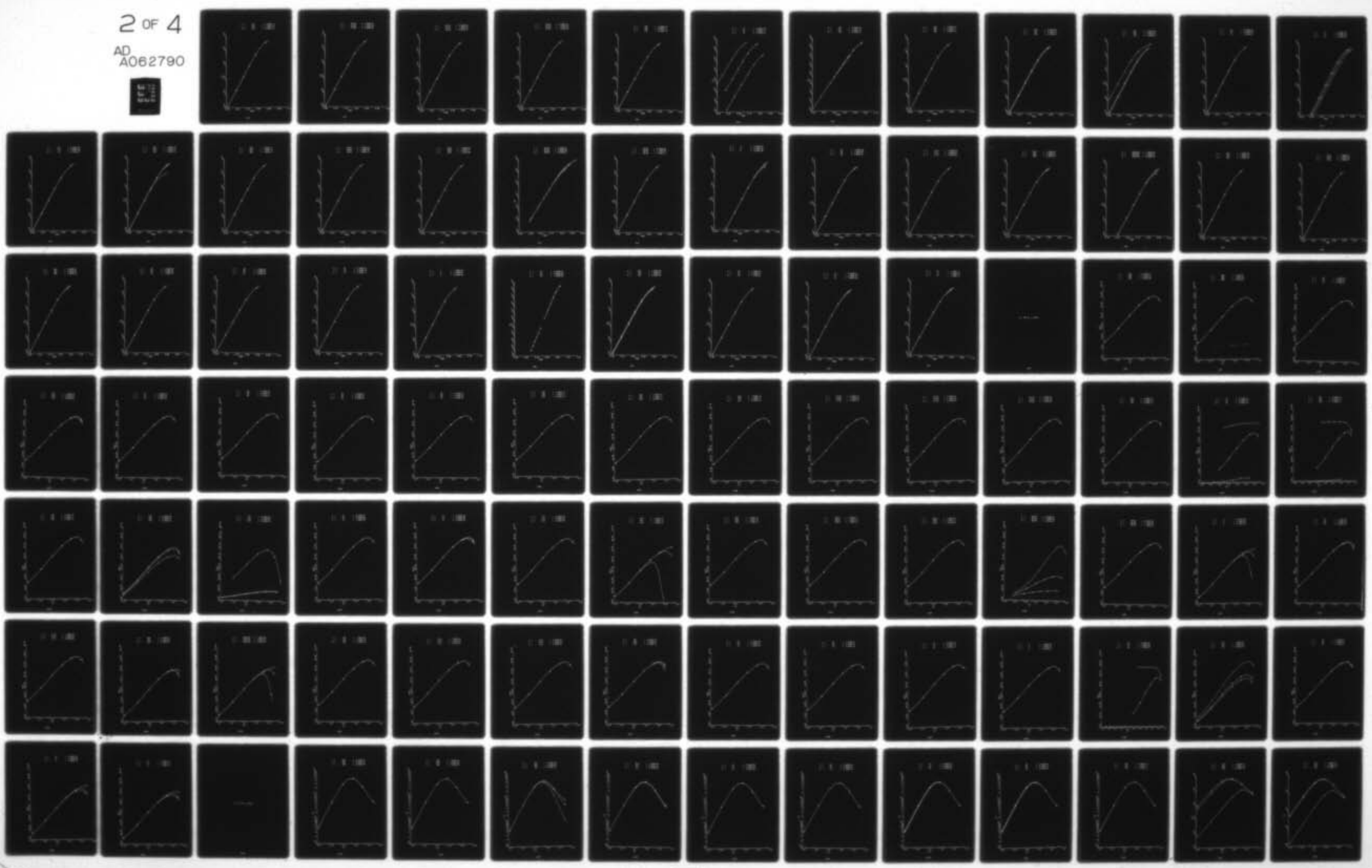
* -- CSO = 4.000E-13
+ -- CSO = 1.000E-11
0 -- CSO = 2.000E-12
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

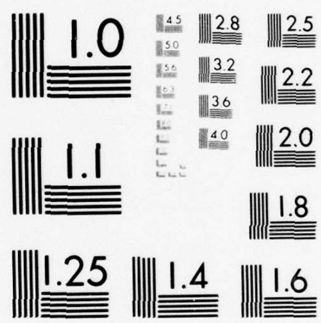

* -- CEO = 4.000E-13
+ -- CEO = 1.000E-11
0 -- CEO = 9.000E-13
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

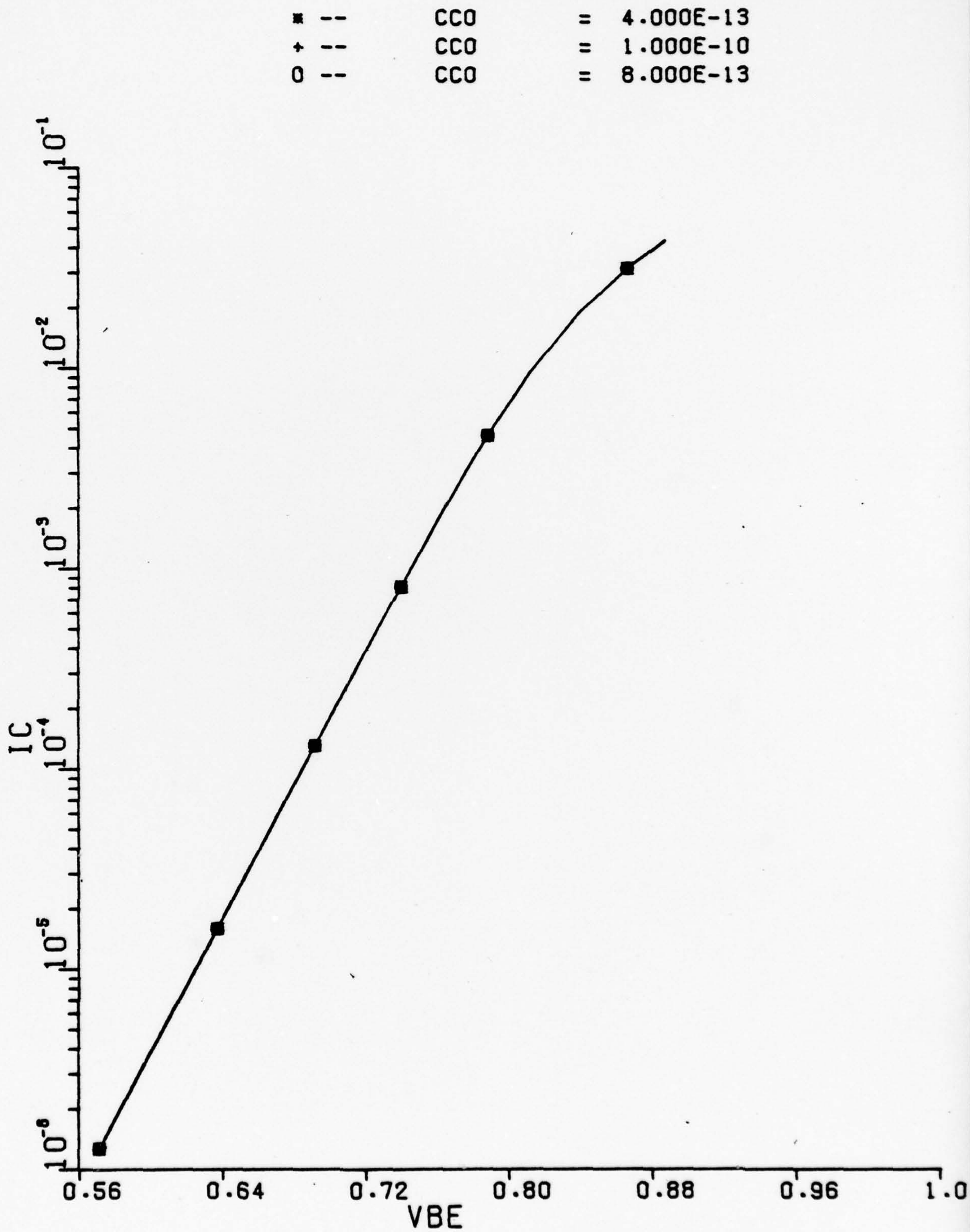
AD-A062 790 TRW DEFENSE AND SPACE SYSTEMS GROUP REDONDO BEACH CALIF F/G 9/1
PROCESS-ORIENTED, HIGH-INJECTION CIRCUIT MODELS FOR INTEGRATED --ETC(U)
JAN 78 J CHOMA N00014-77-C-0043
UNCLASSIFIED TRW-78.4734.7-023-PT-2-VO NL

2 OF 4

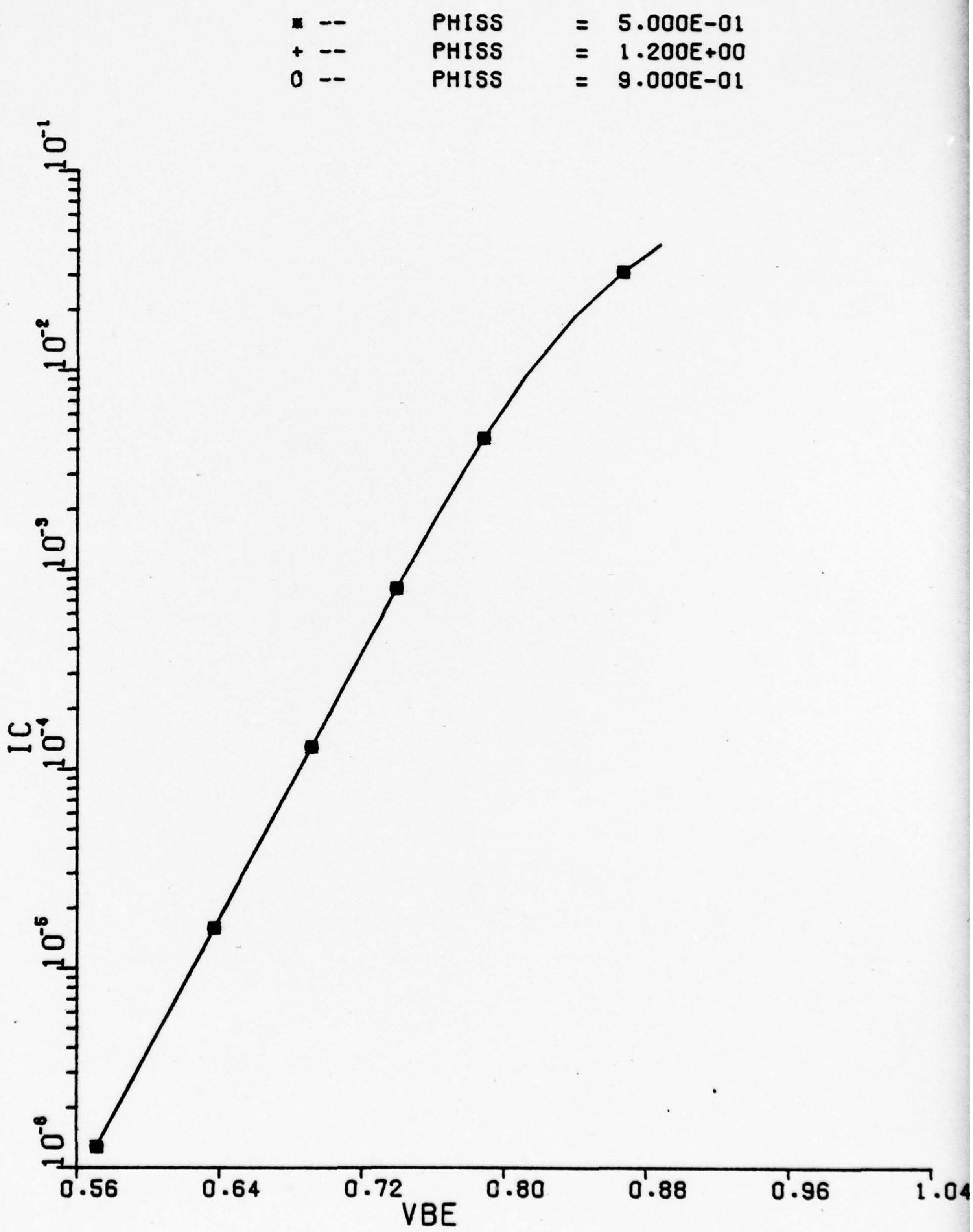
AD
A062790



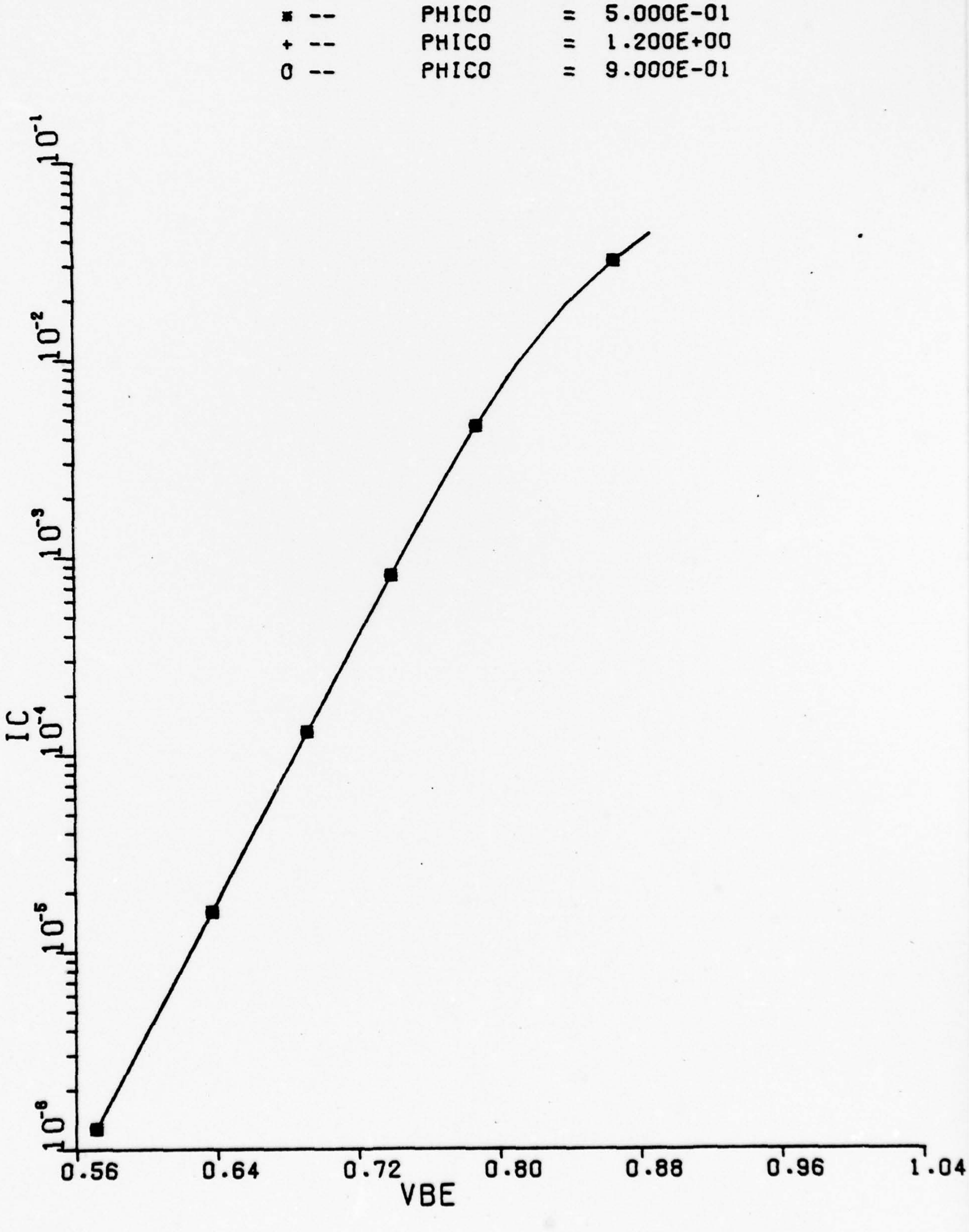

1.0
4.5
5.0
5.6
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6



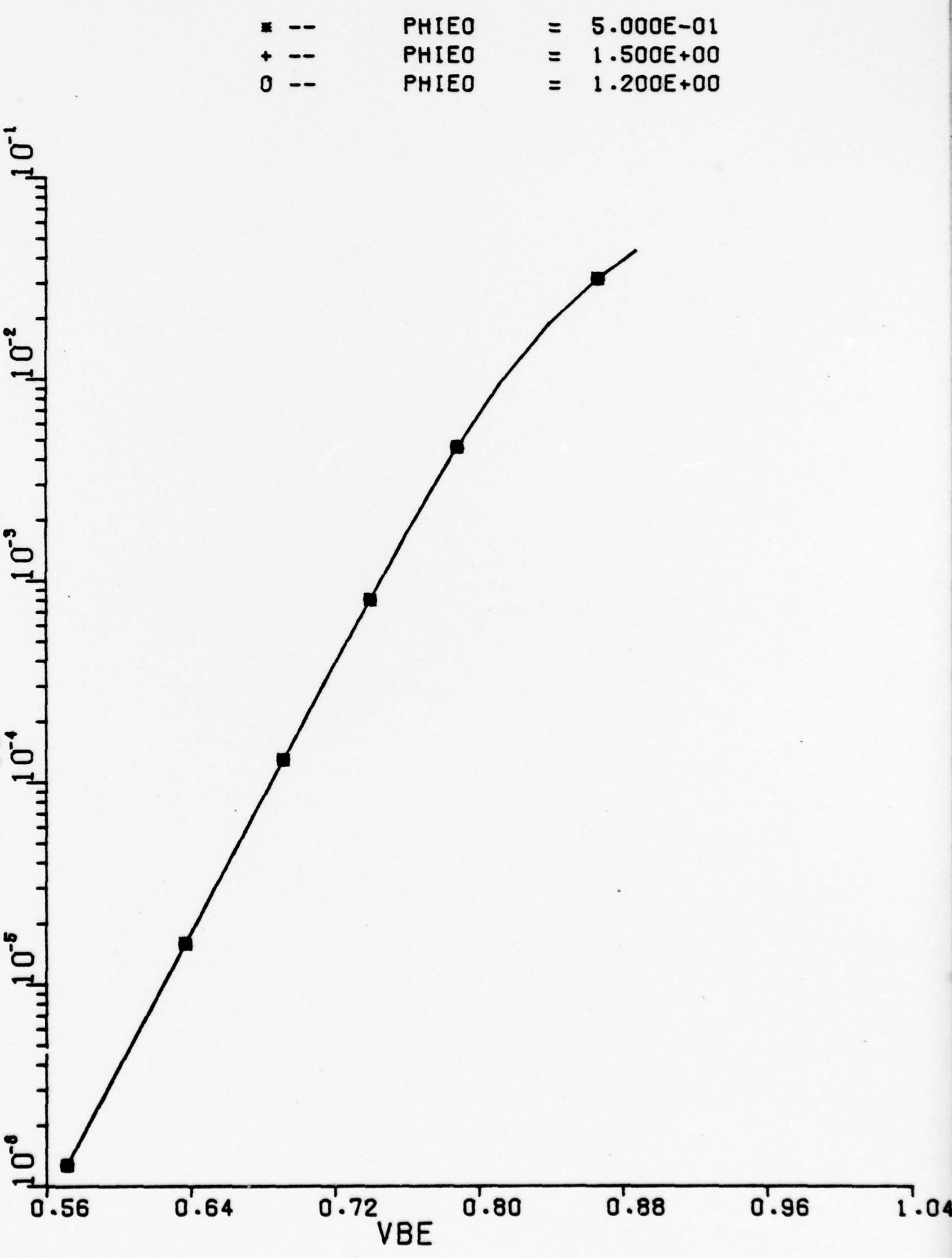
* -- CCO = 4.000E-13
+ -- CCO = 1.000E-10
0 -- CCO = 8.000E-13
IC
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0.56
0.64
0.72
0.80
0.88
0.96
1.0
VBE

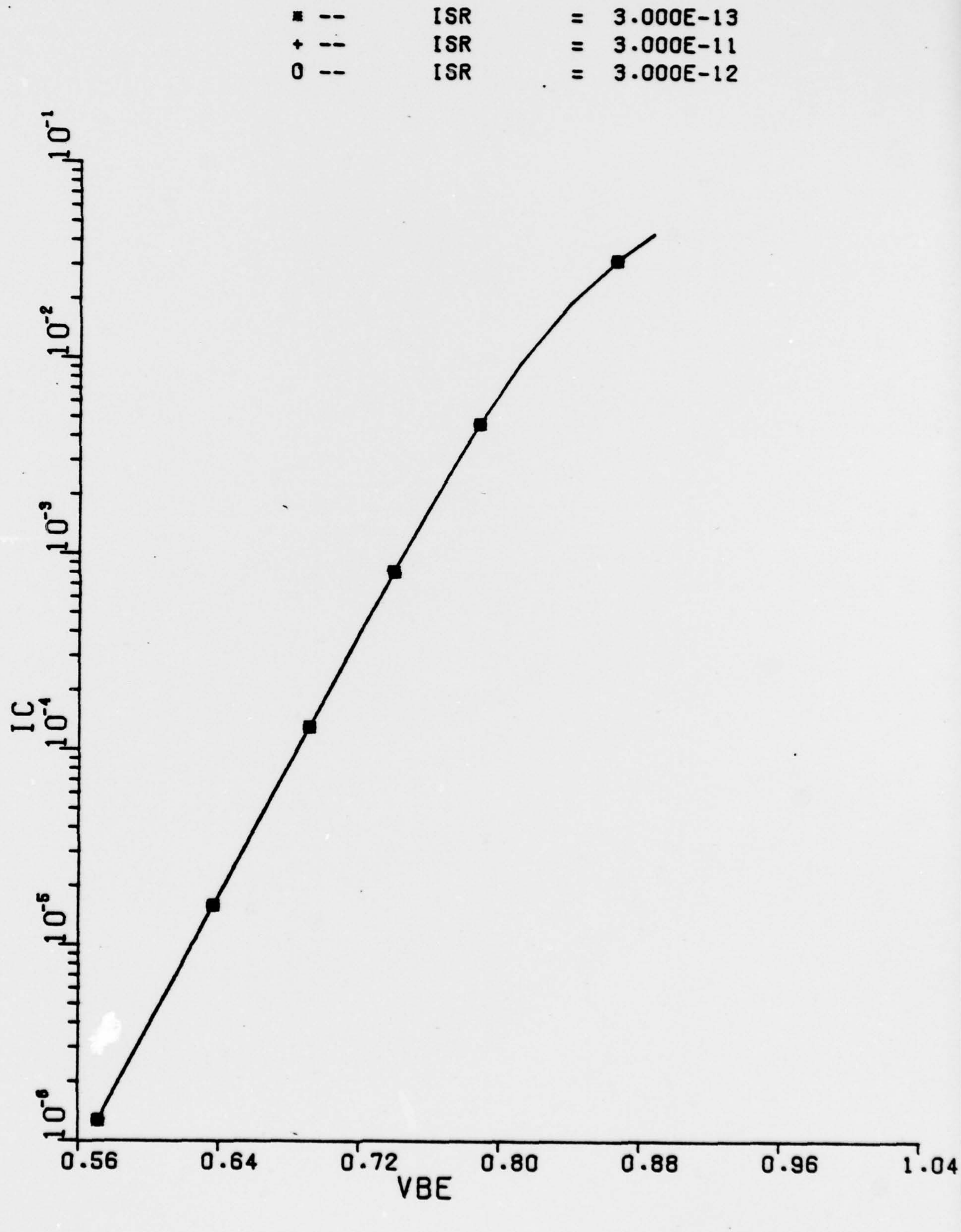


* -- PHISS = 5.000E-01
+ -- PHISS = 1.200E+00
O -- PHISS = 9.000E-01
IC
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

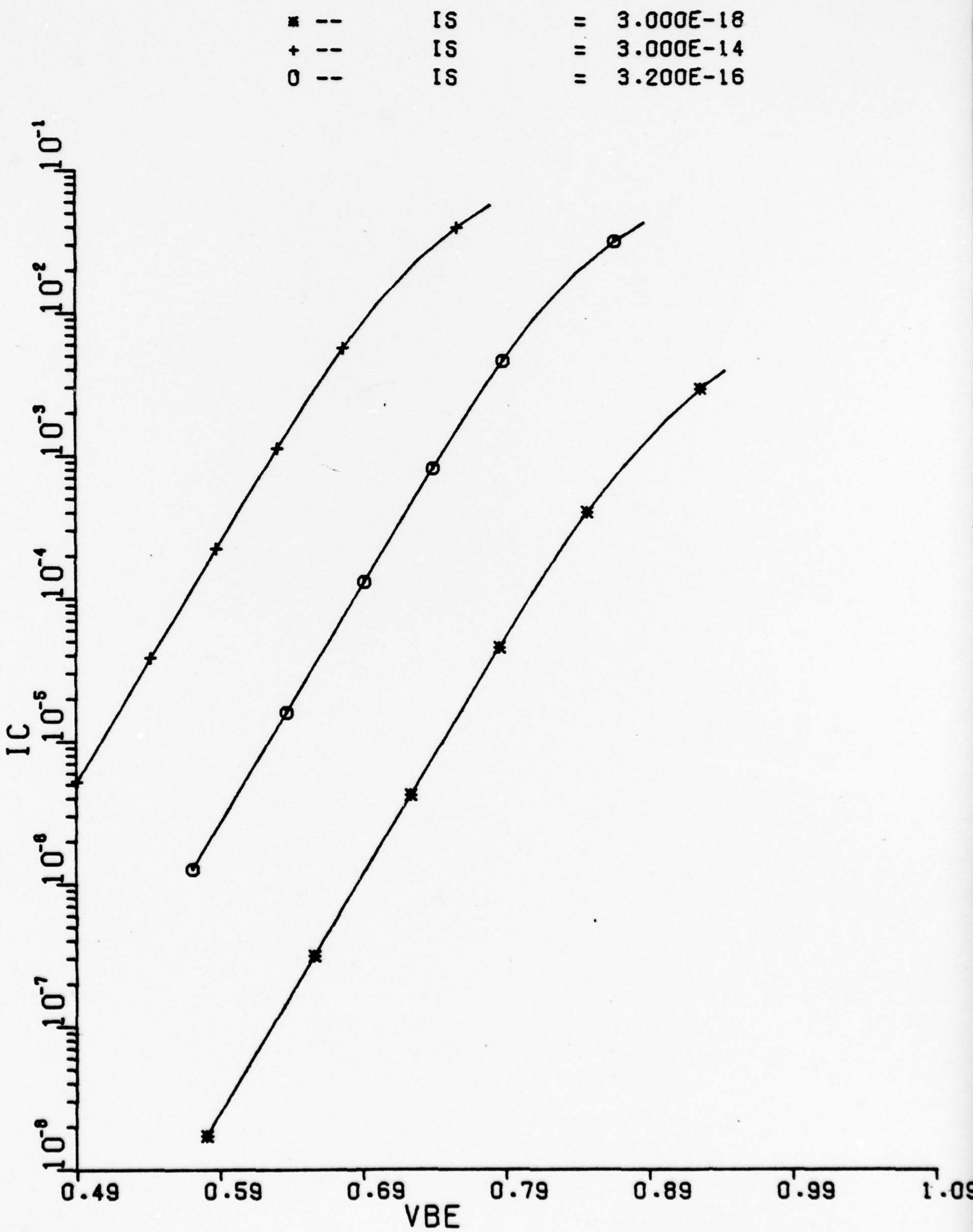


* -- PHICO = 5.000E-01
+ -- PHICO = 1.200E+00
0 -- PHICO = 9.000E-01
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

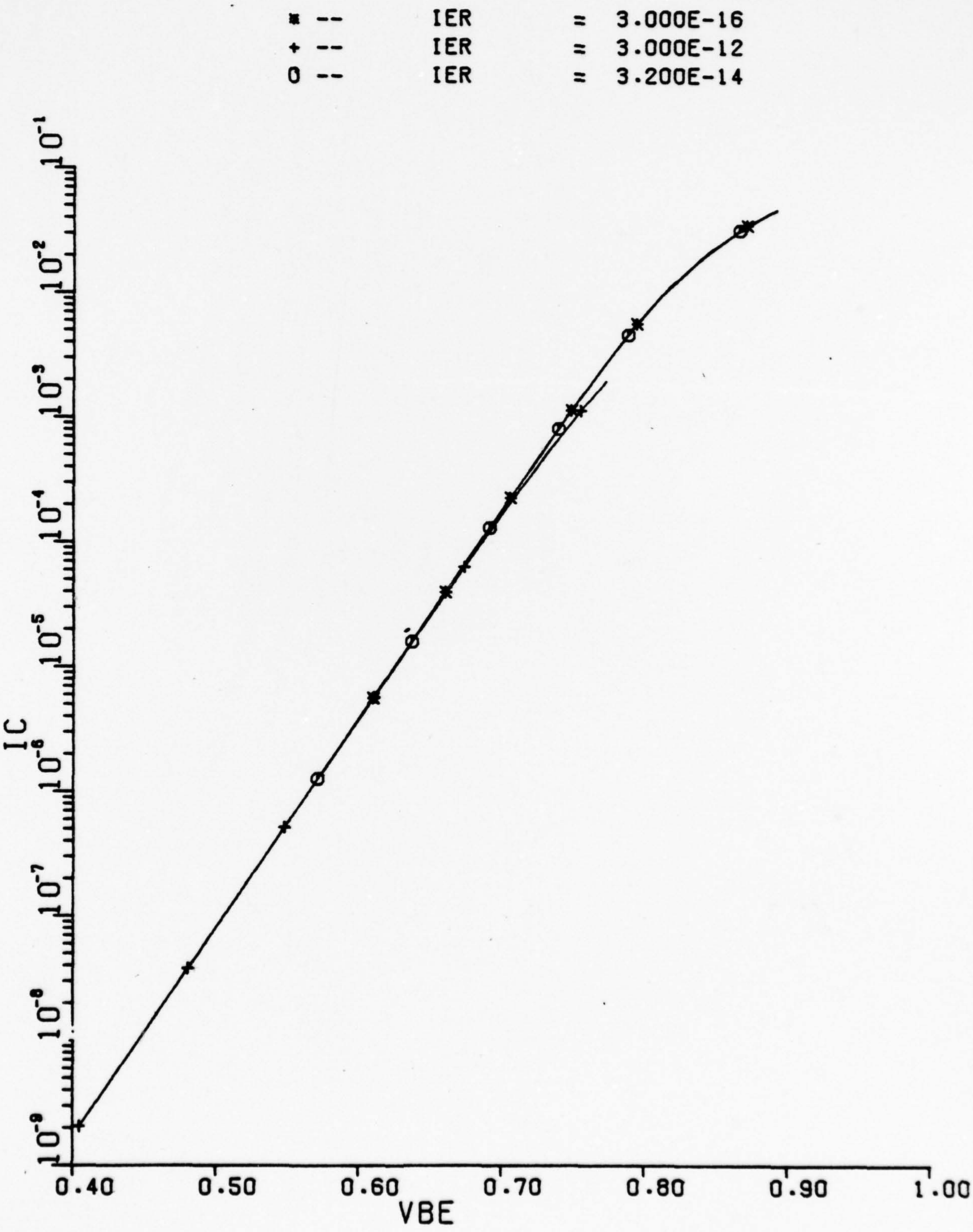

* -- PHIEO = 5.000E-01
+ -- PHIEO = 1.500E+00
0 -- PHIEO = 1.200E+00
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04



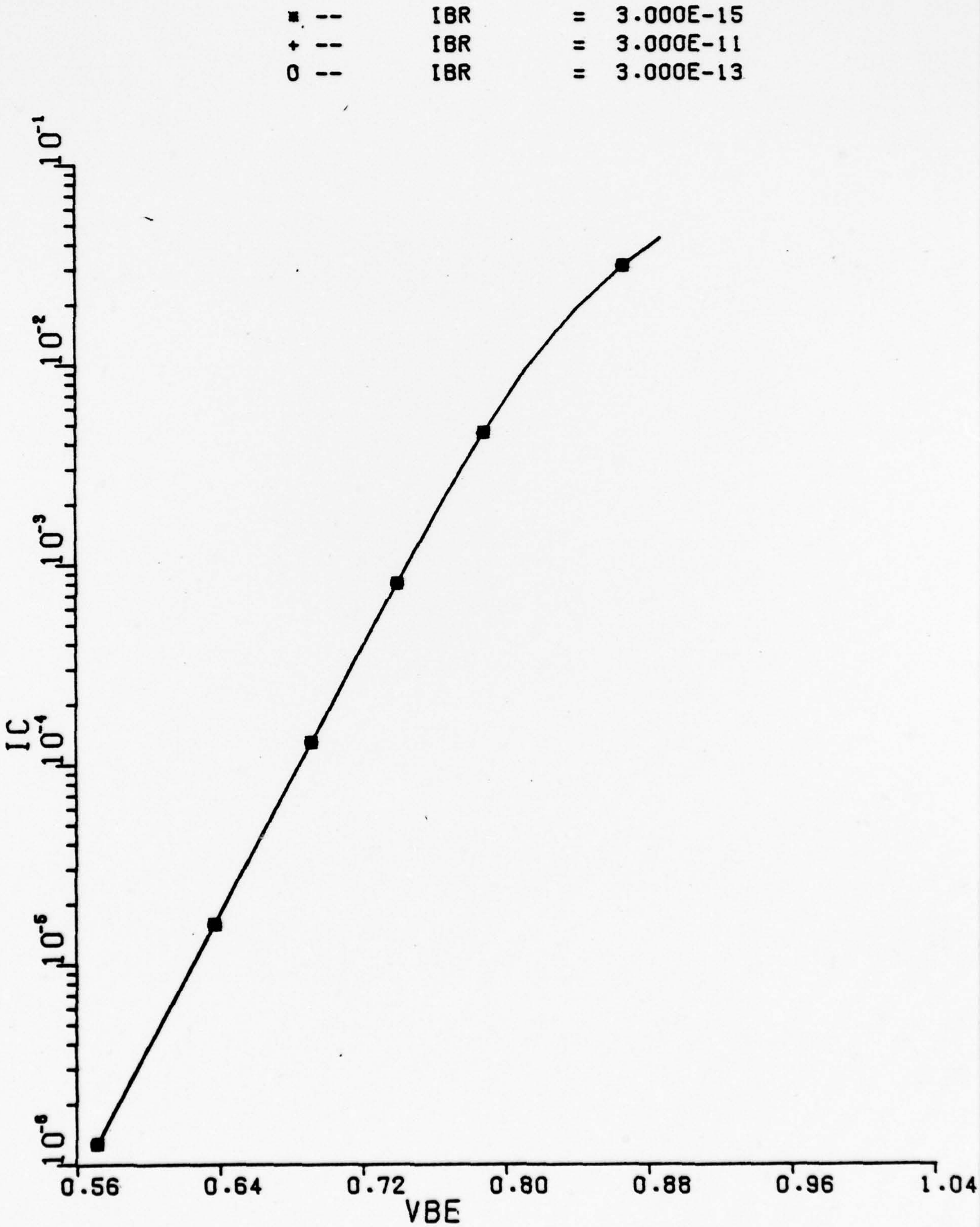
* -- ISR = 3.000E-13
+ -- ISR = 3.000E-11
0 -- ISR = 3.000E-12
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



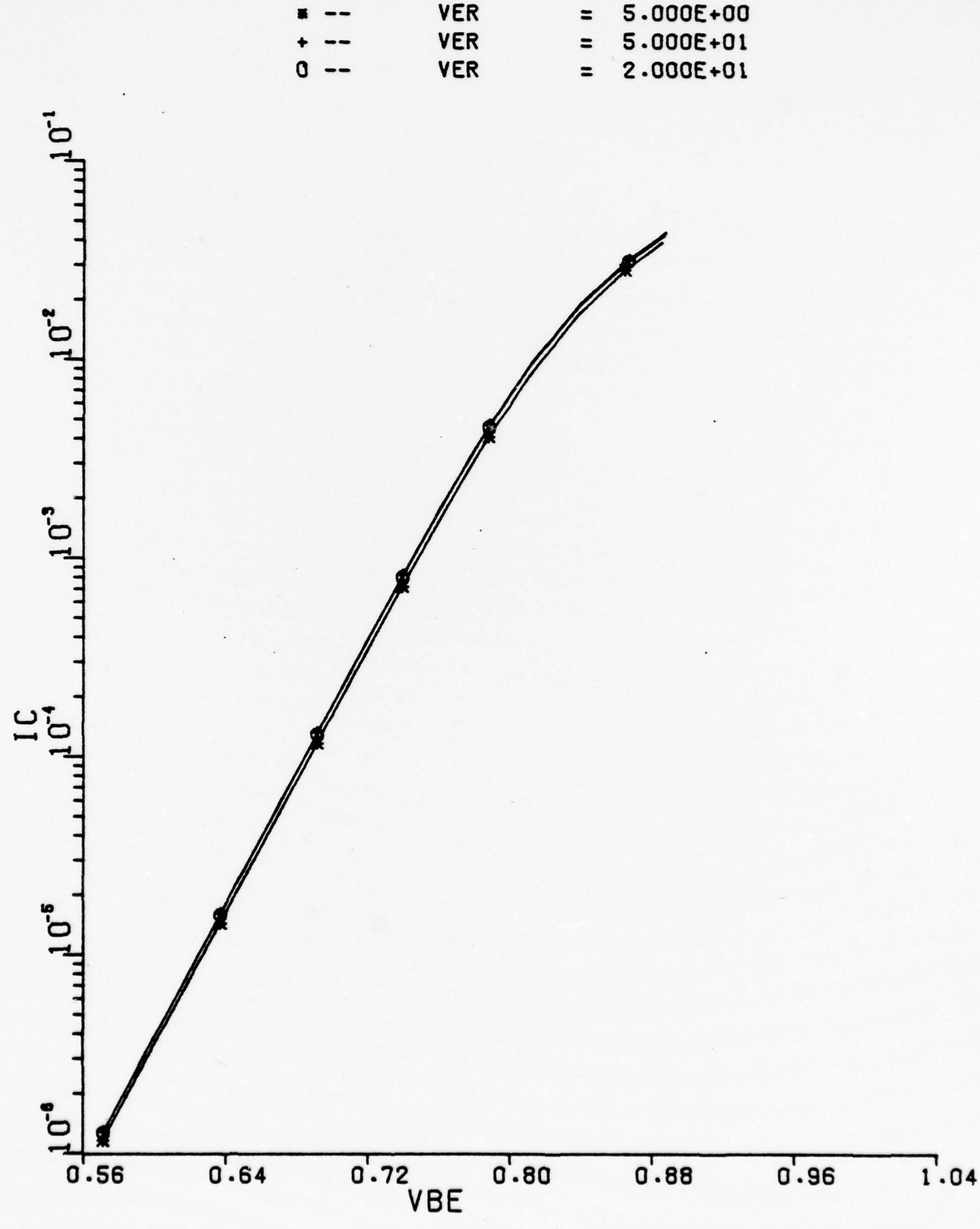
* -- IS = 3.000E-18
+ -- IS = 3.000E-14
O -- IS = 3.200E-16
IC
VBE
0.49
0.59
0.69
0.79
0.89
0.99
1.09



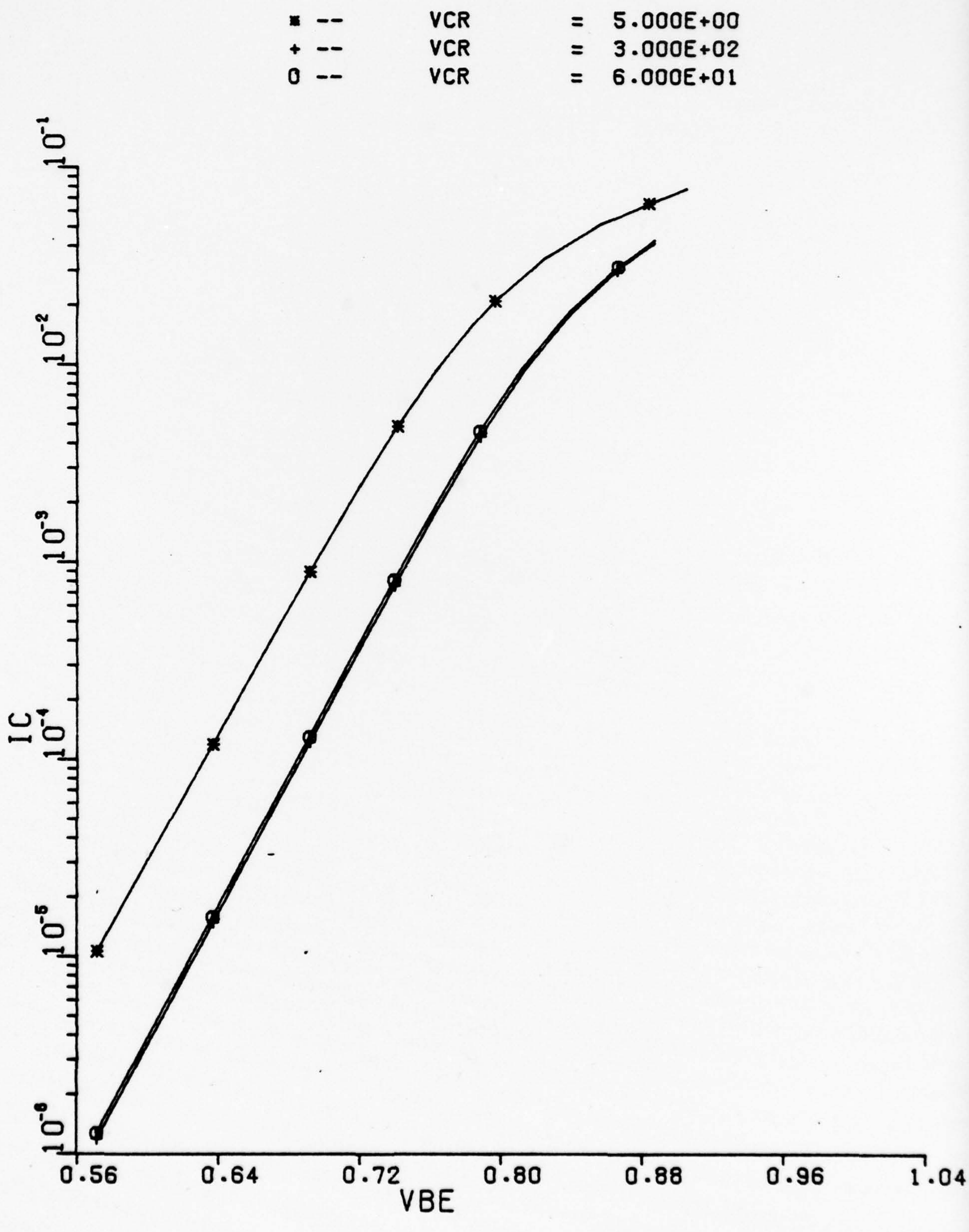
* -- IER = 3.000E-16
+ -- IER = 3.000E-12
O -- IER = 3.200E-14
IC
VBE
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
0.40
0.50
0.60
0.70
0.80
0.90
1.00



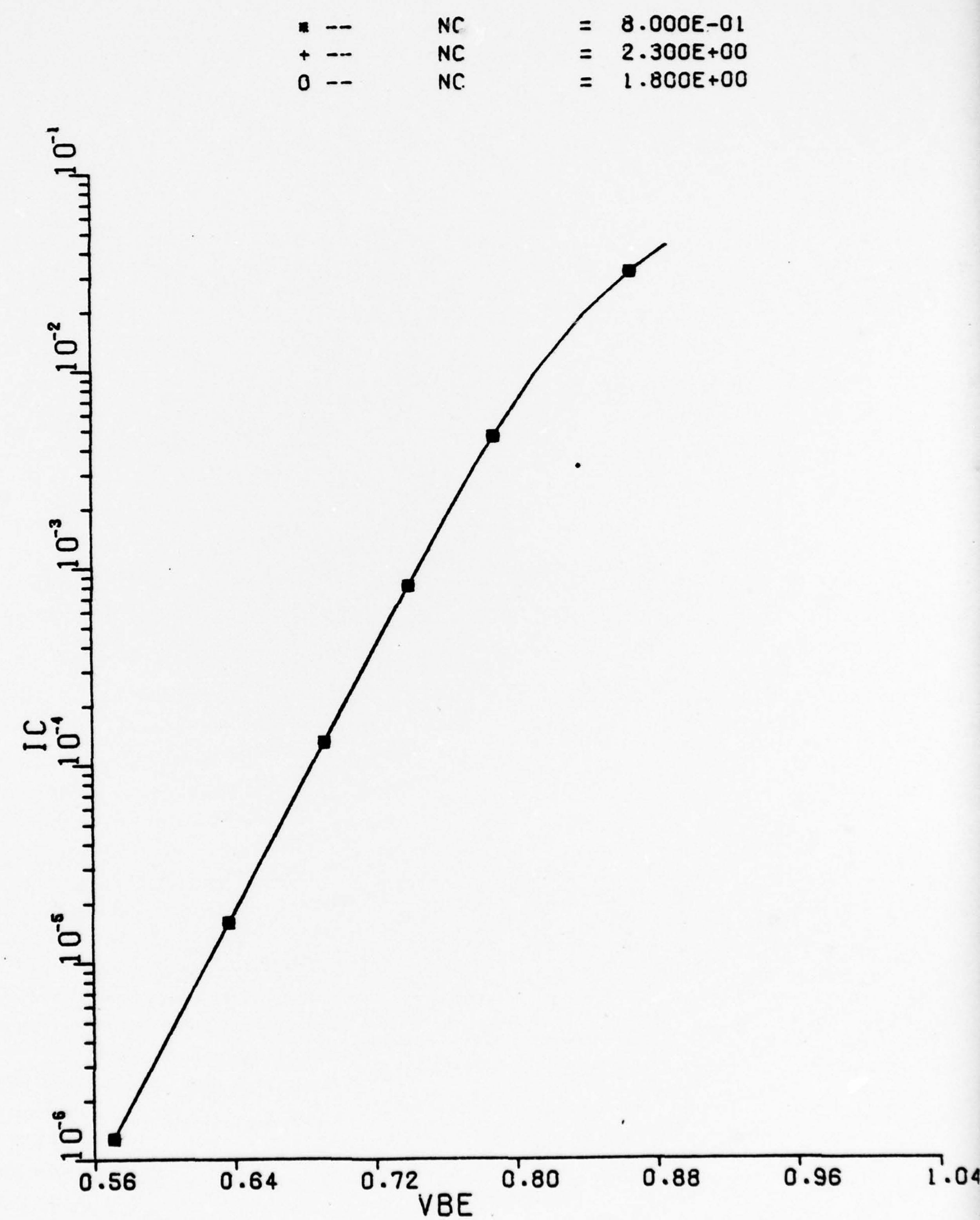
* -- IBR = 3.000E-15
+ -- IBR = 3.000E-11
0 -- IBR = 3.000E-13
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



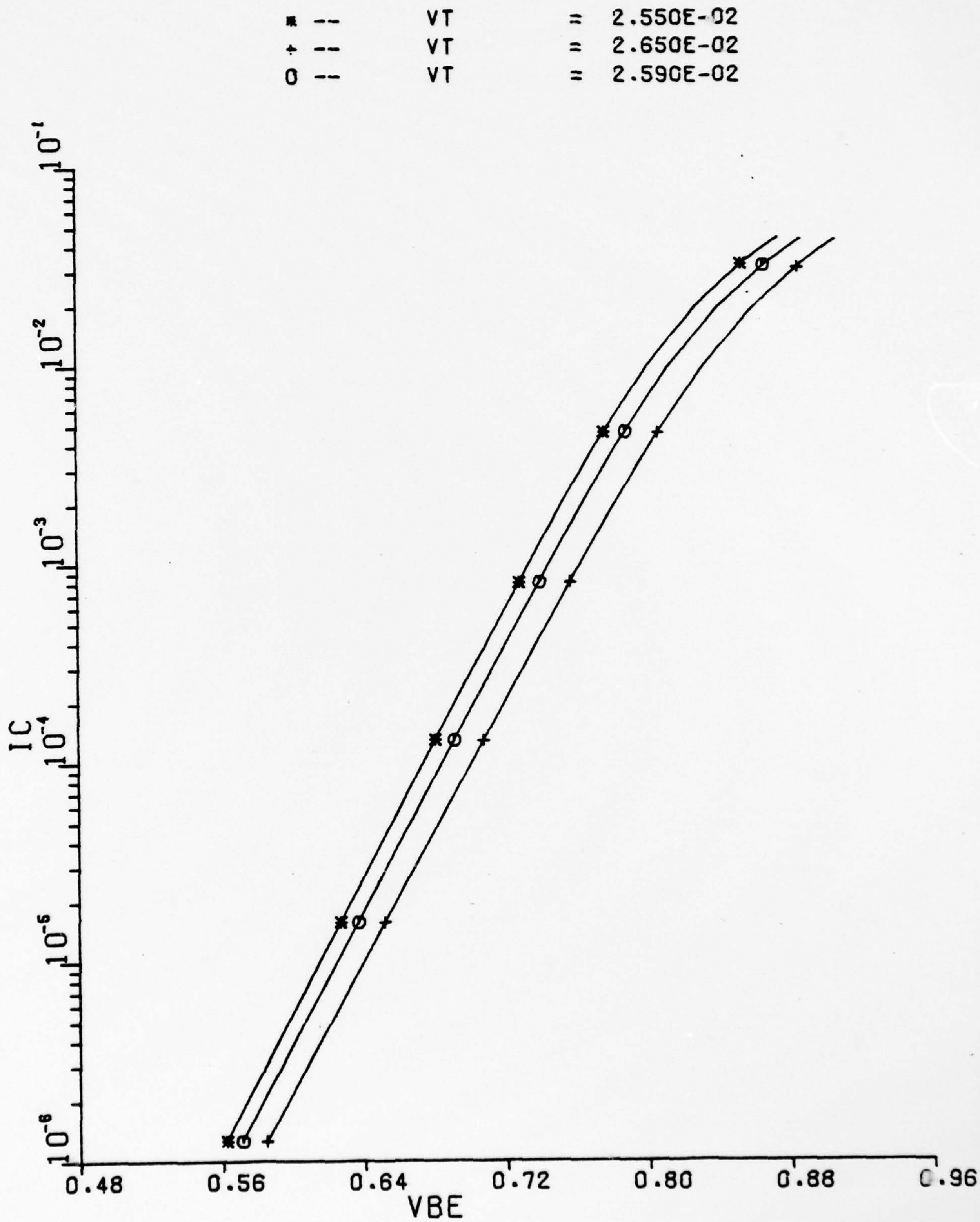
* -- VER = 5.000E+00
+ -- VER = 5.000E+01
0 -- VER = 2.000E+01
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



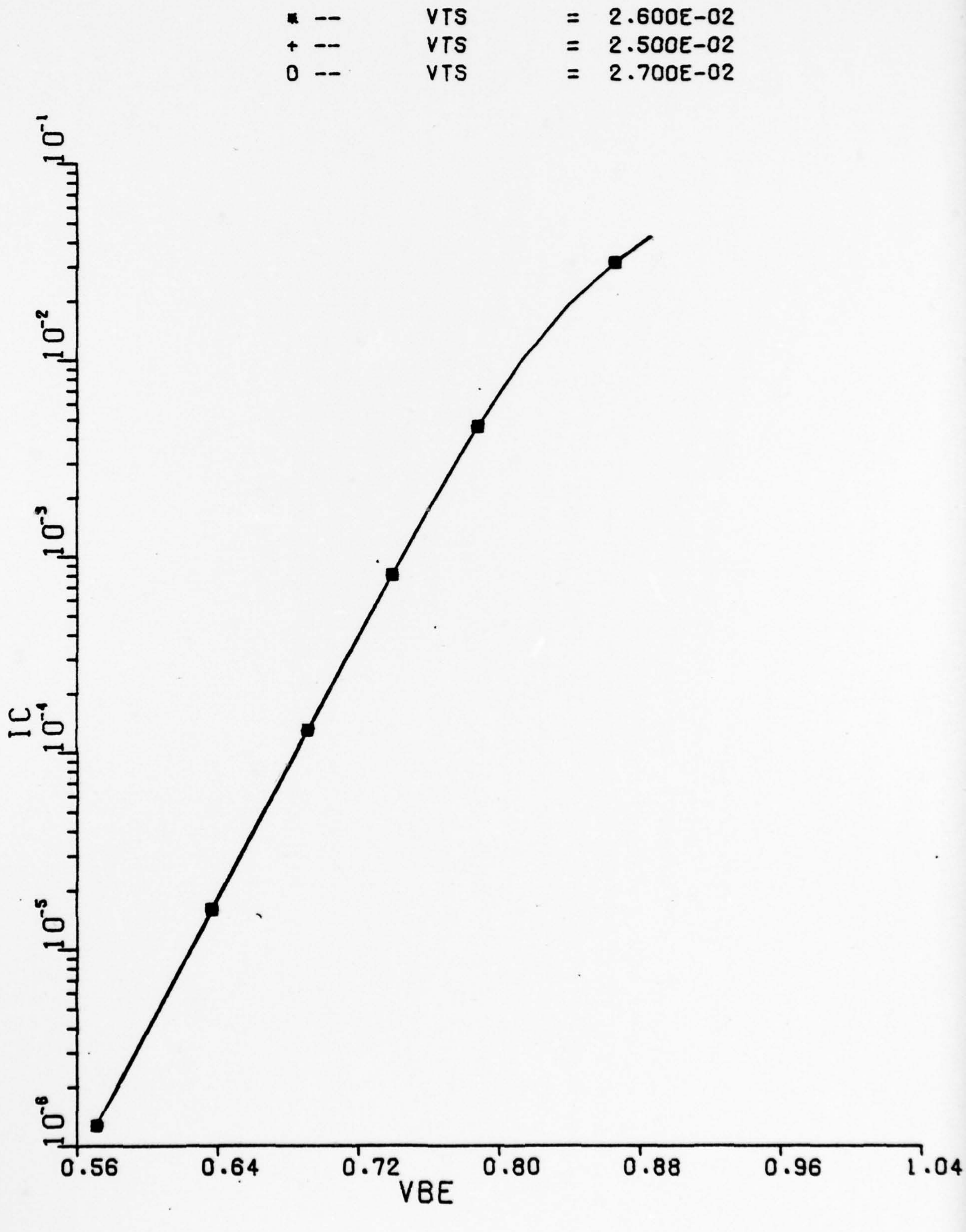
* -- VCR = 5.000E+00
+ -- VCR = 3.000E+02
0 -- VCR = 6.000E+01
IC
VBE
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.56
0.64
0.72
0.80
0.88
0.96
1.04



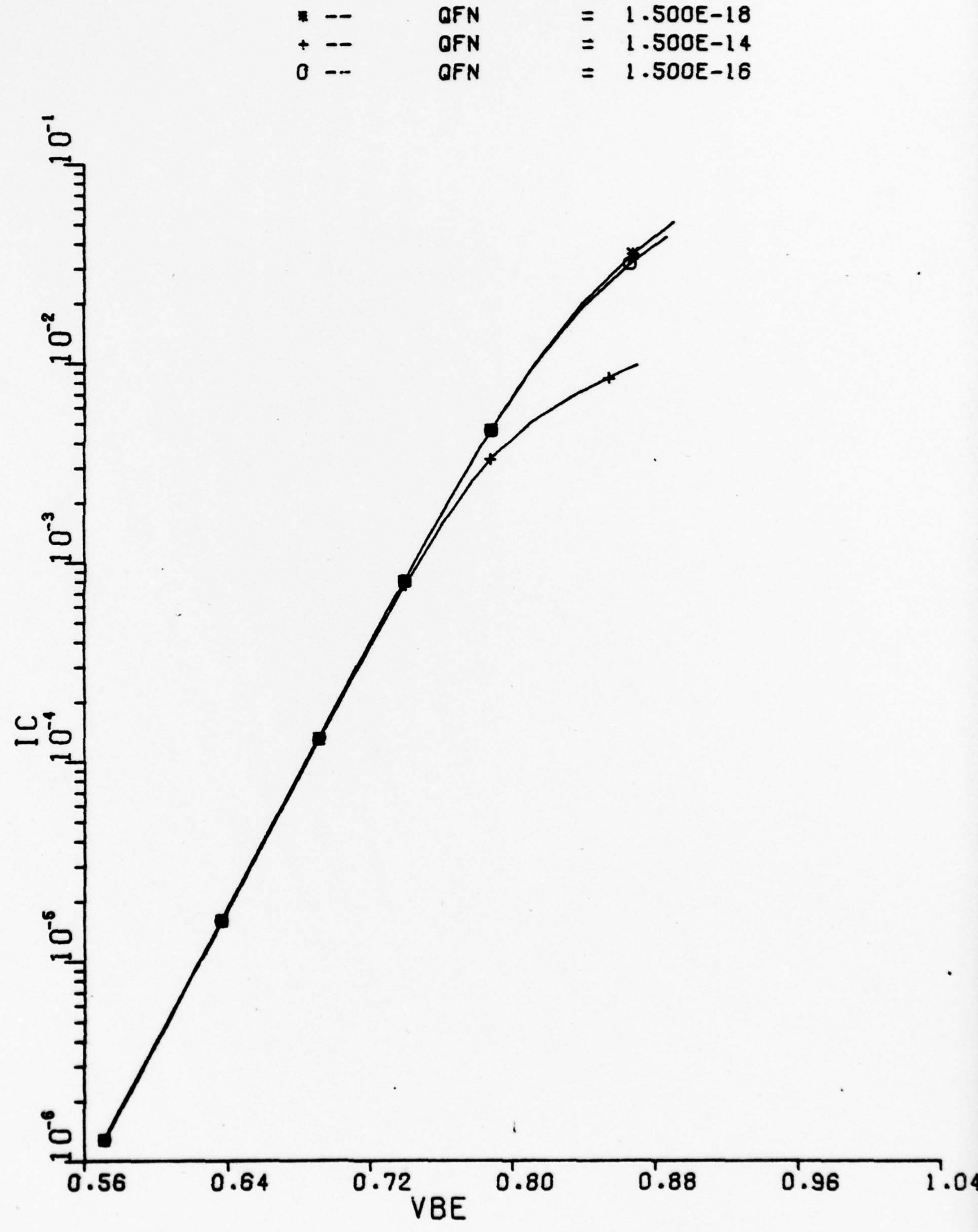
■ -- NC = 8.000E-01
+ -- NC = 2.300E+00
0 -- NC = 1.800E+00
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

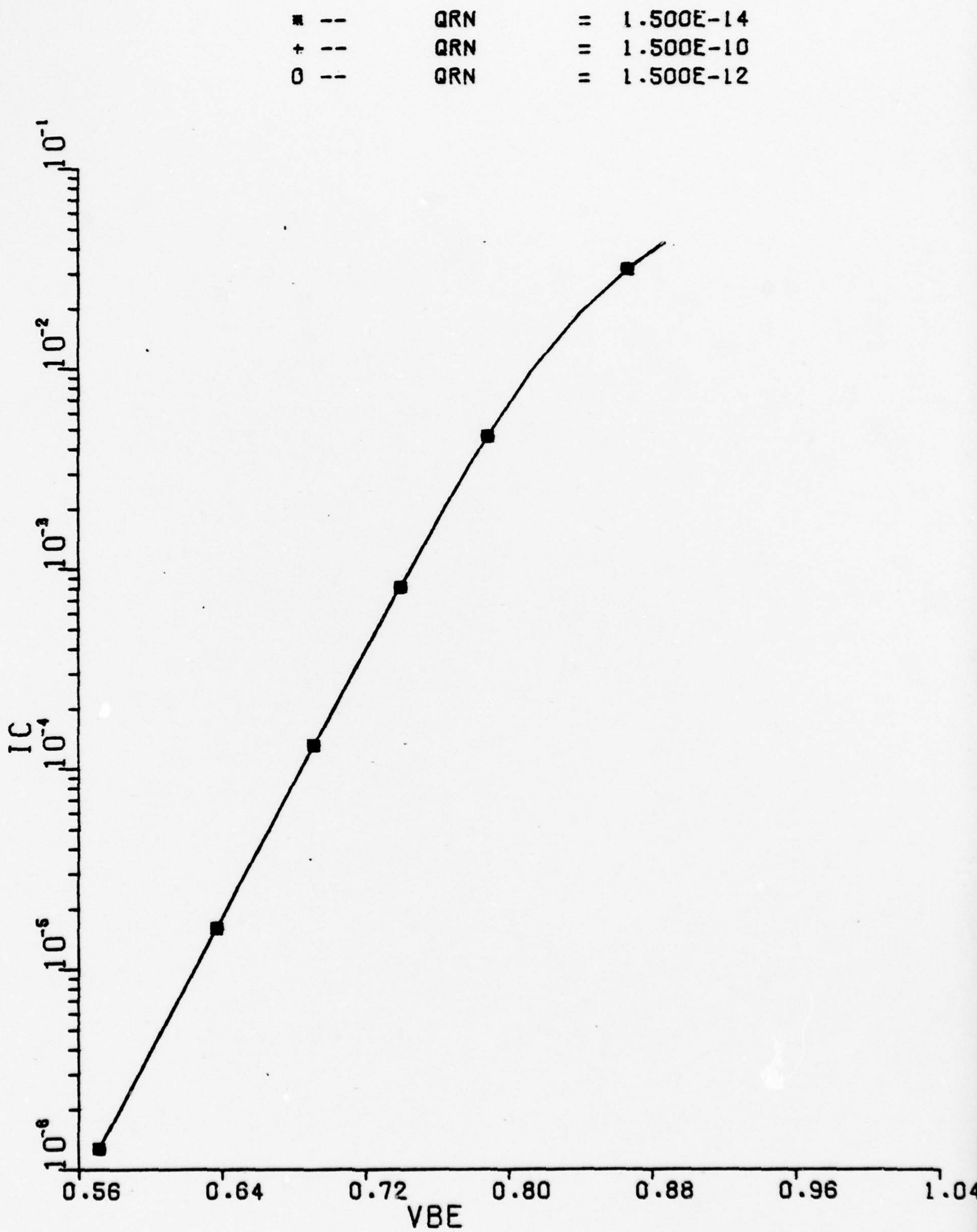


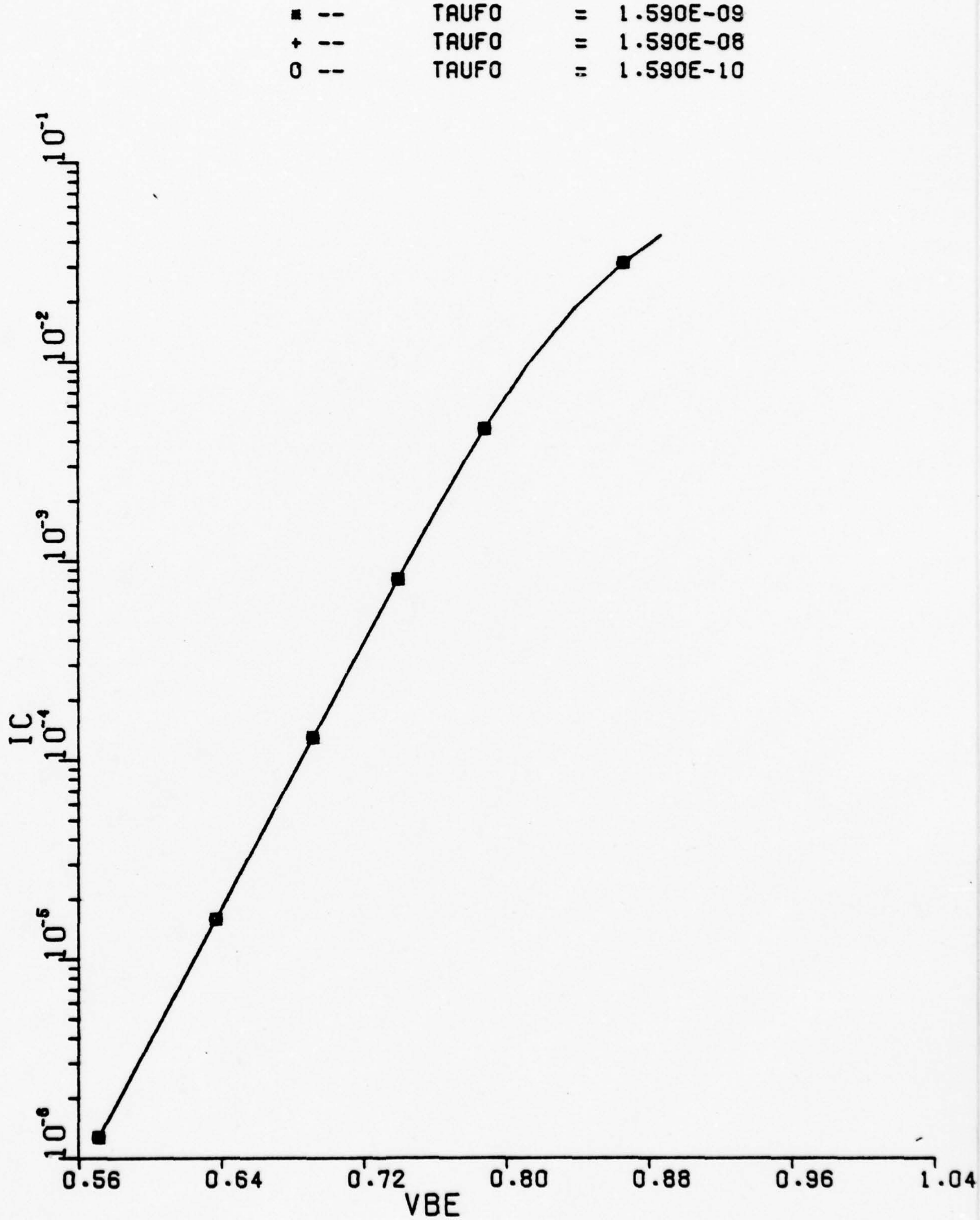
* -- VT = 2.550E-02
+ -- VT = 2.650E-02
O -- VT = 2.590E-02
IC
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
0.48
0.56
0.64
0.72
0.80
0.88
0.96
VBE



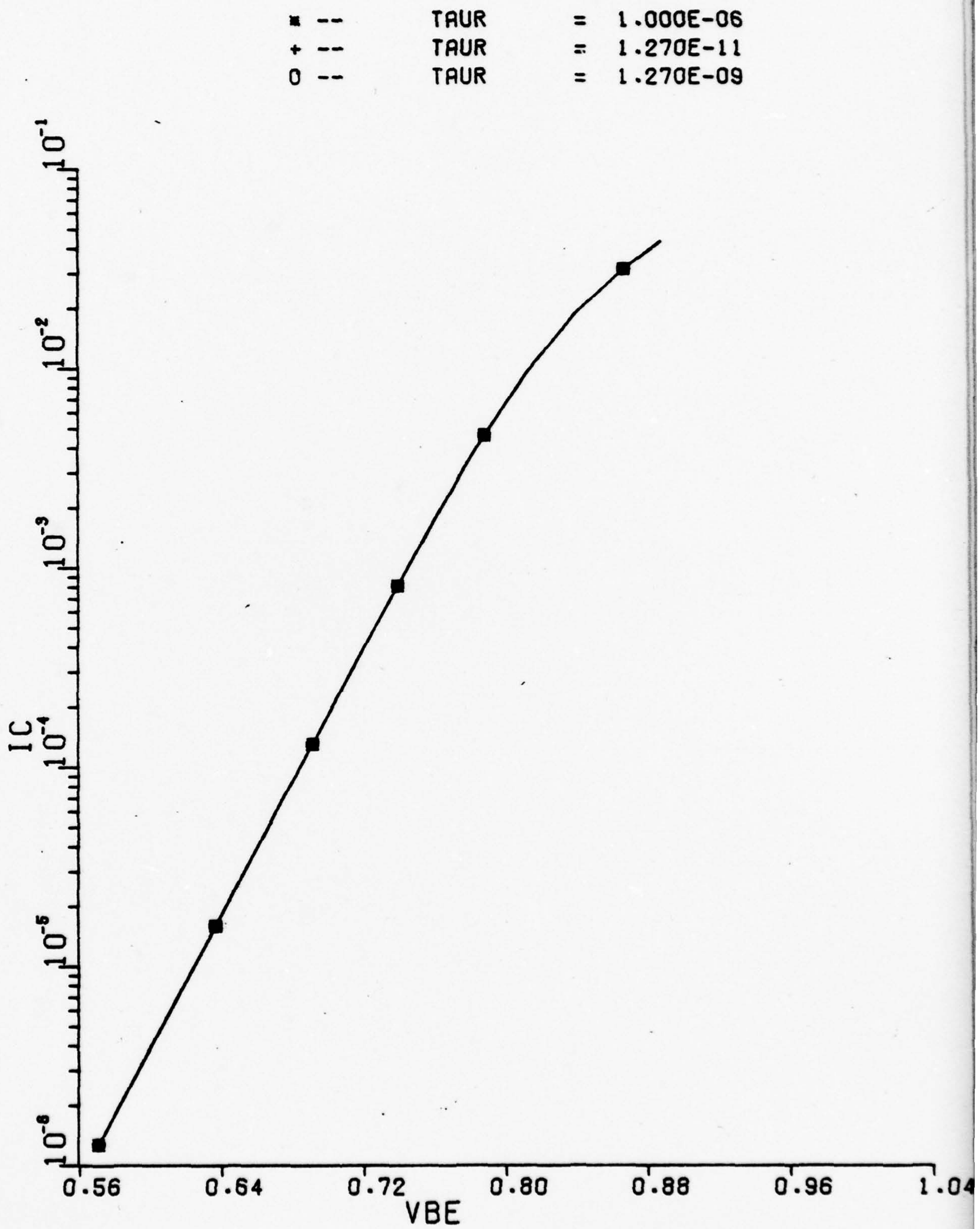
* -- VTS = 2.600E-02
+ -- VTS = 2.500E-02
0 -- VTS = 2.700E-02
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04


* -- QFN = 1.500E-18
+ -- QFN = 1.500E-14
O -- QFN = 1.500E-16
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

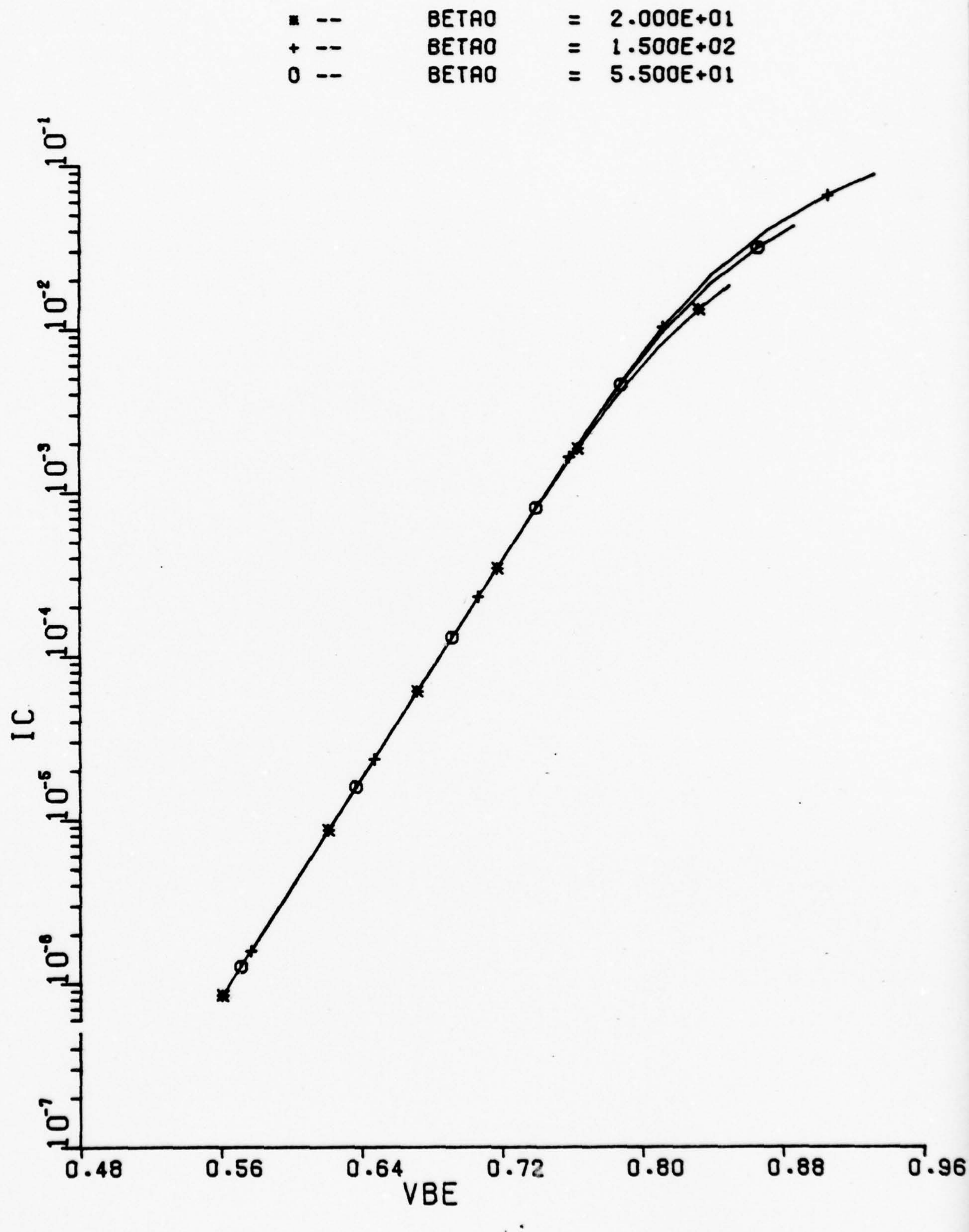

* -- QRN = 1.500E-14
+ -- QRN = 1.500E-10
O -- QRN = 1.500E-12
IC
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04



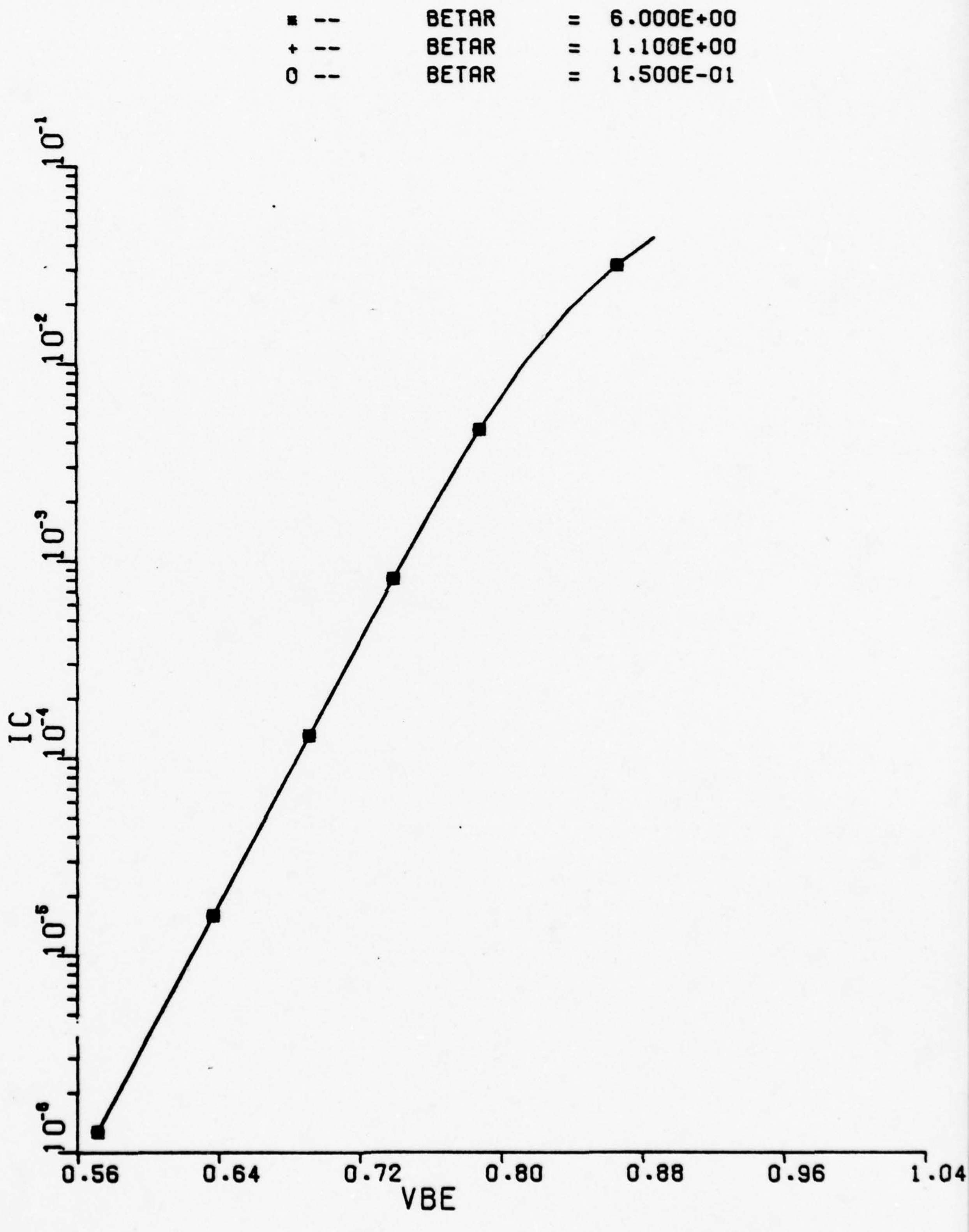
■ -- TAUFO = 1.590E-09
+ -- TAUFO = 1.590E-08
O -- TAUFO = 1.590E-10
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

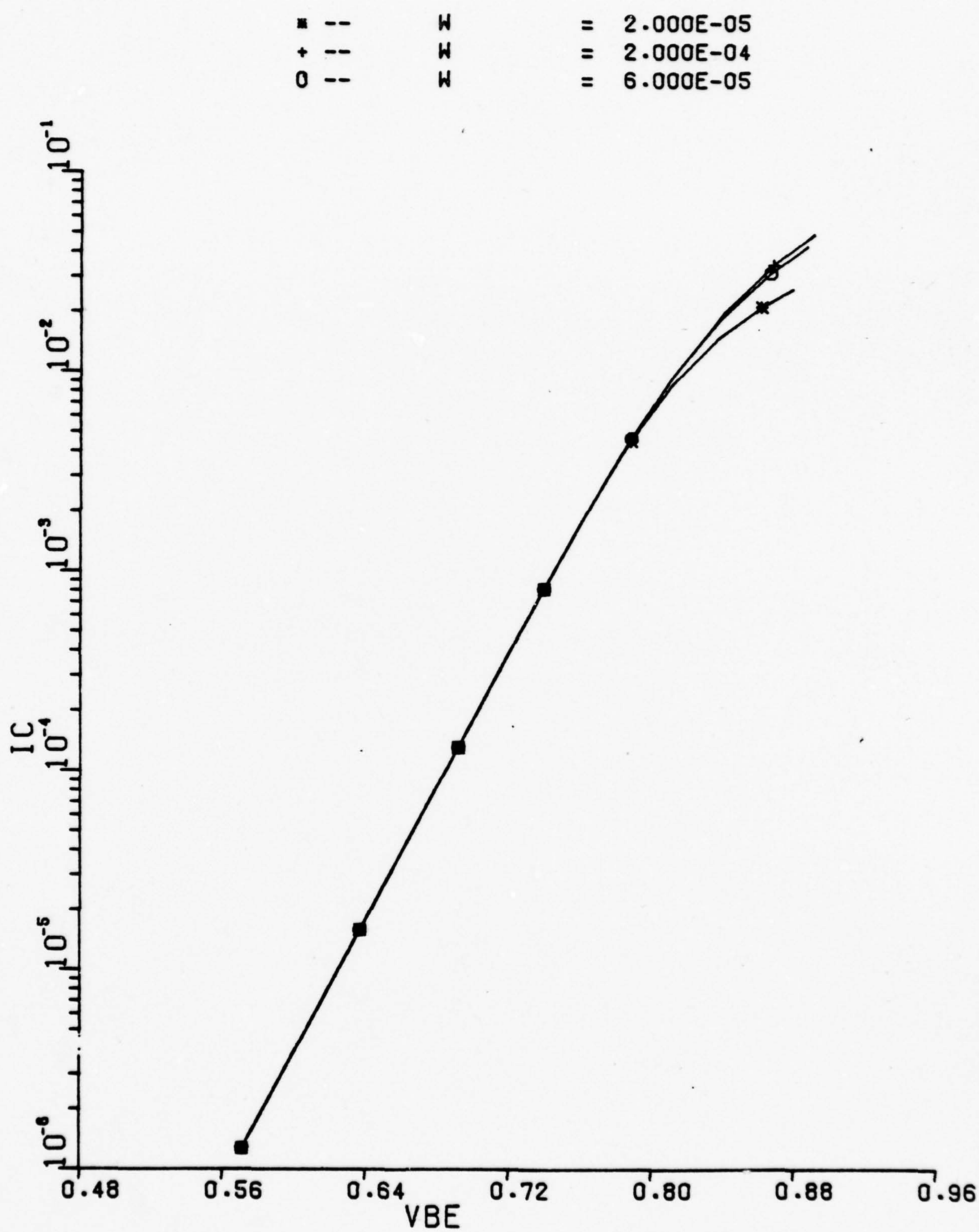


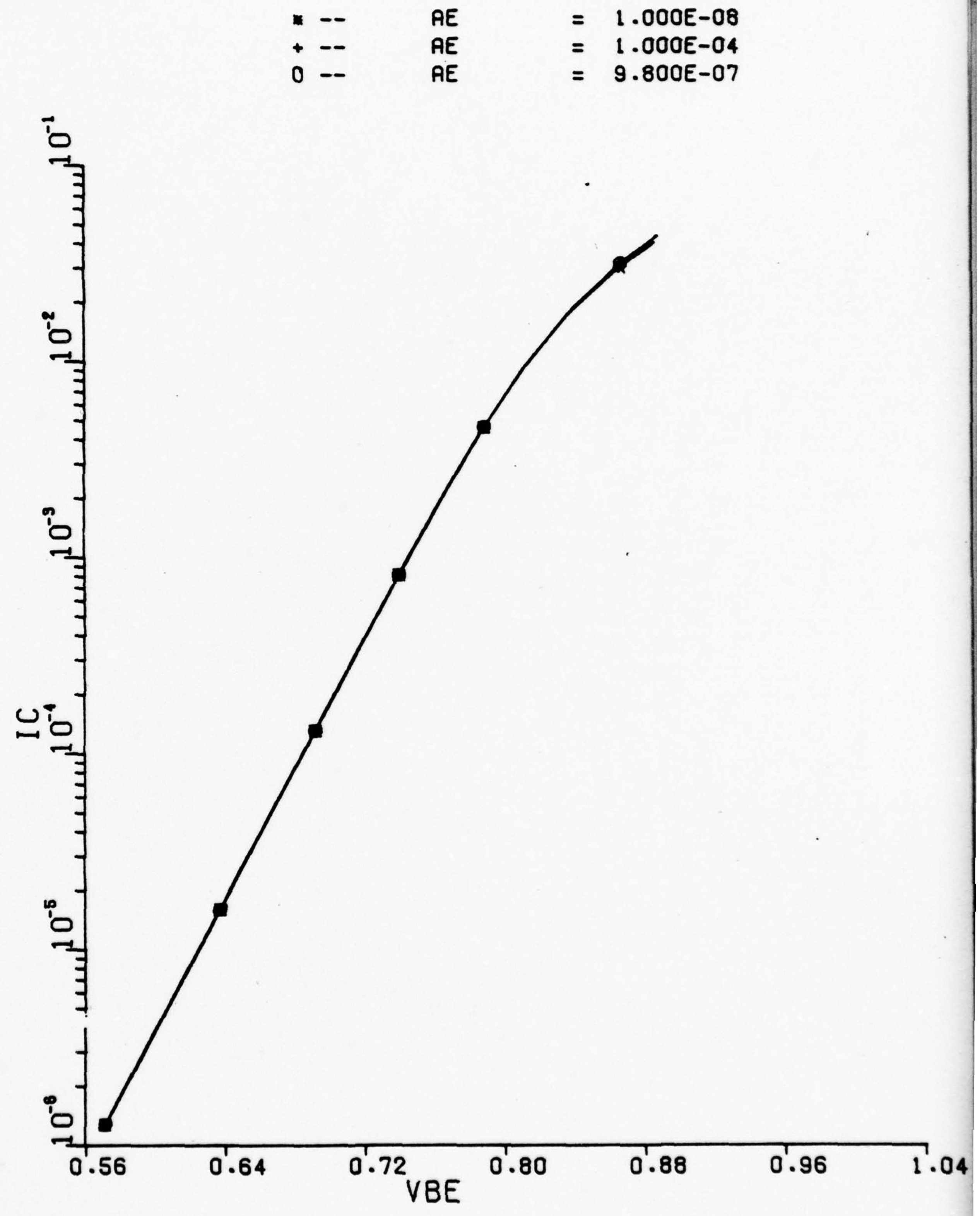
* -- TAUR = 1.000E-06
+ -- TAUR = 1.270E-11
0 -- TAUR = 1.270E-09
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04



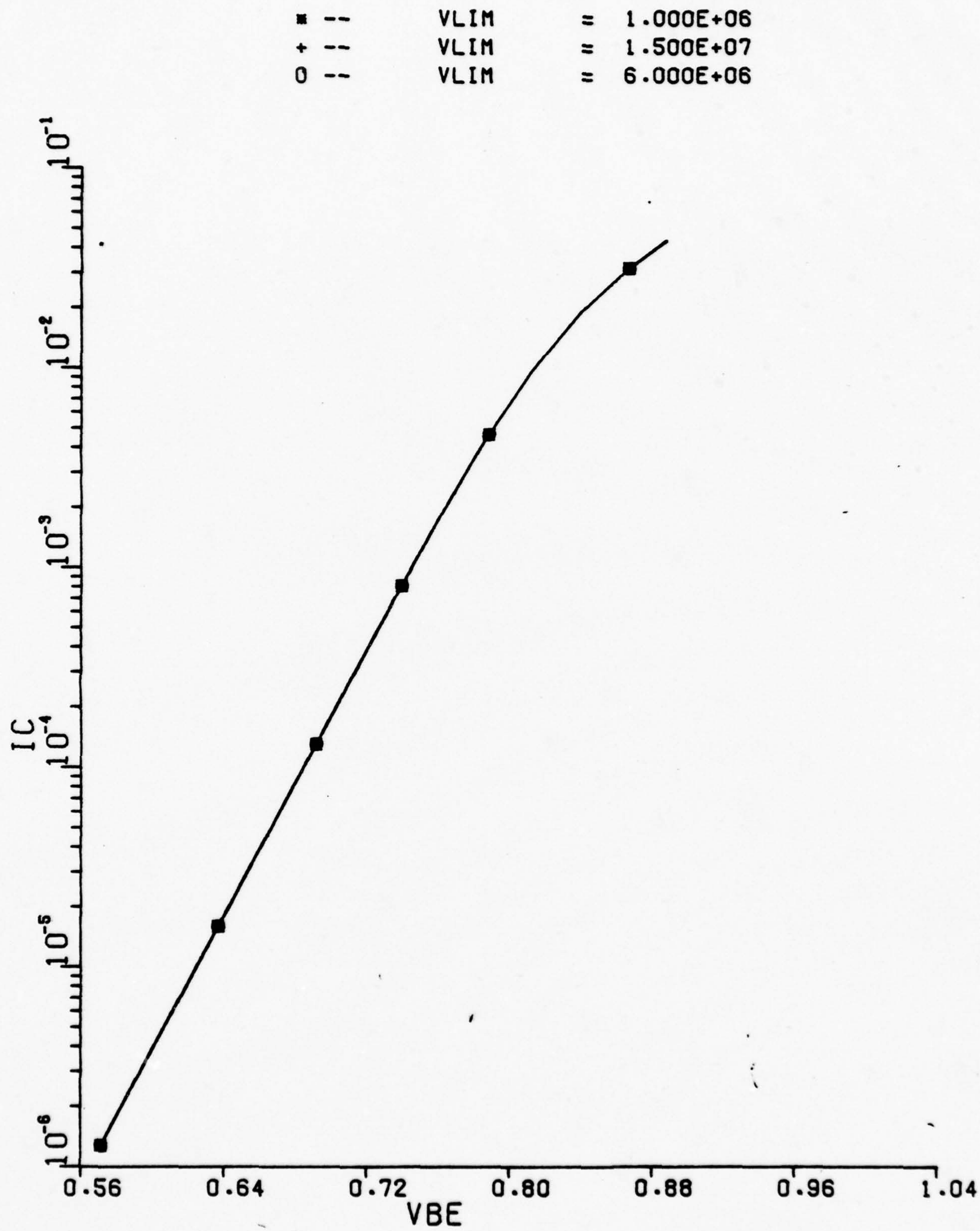
* -- BETAO = 2.000E+01
+ -- BETAO = 1.500E+02
0 -- BETAO = 5.500E+01
IC
VBE
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
0.48
0.56
0.64
0.72
0.80
0.88
0.96


* -- BETAR = 6.000E+00
+ -- BETAR = 1.100E+00
0 -- BETAR = 1.500E-01
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

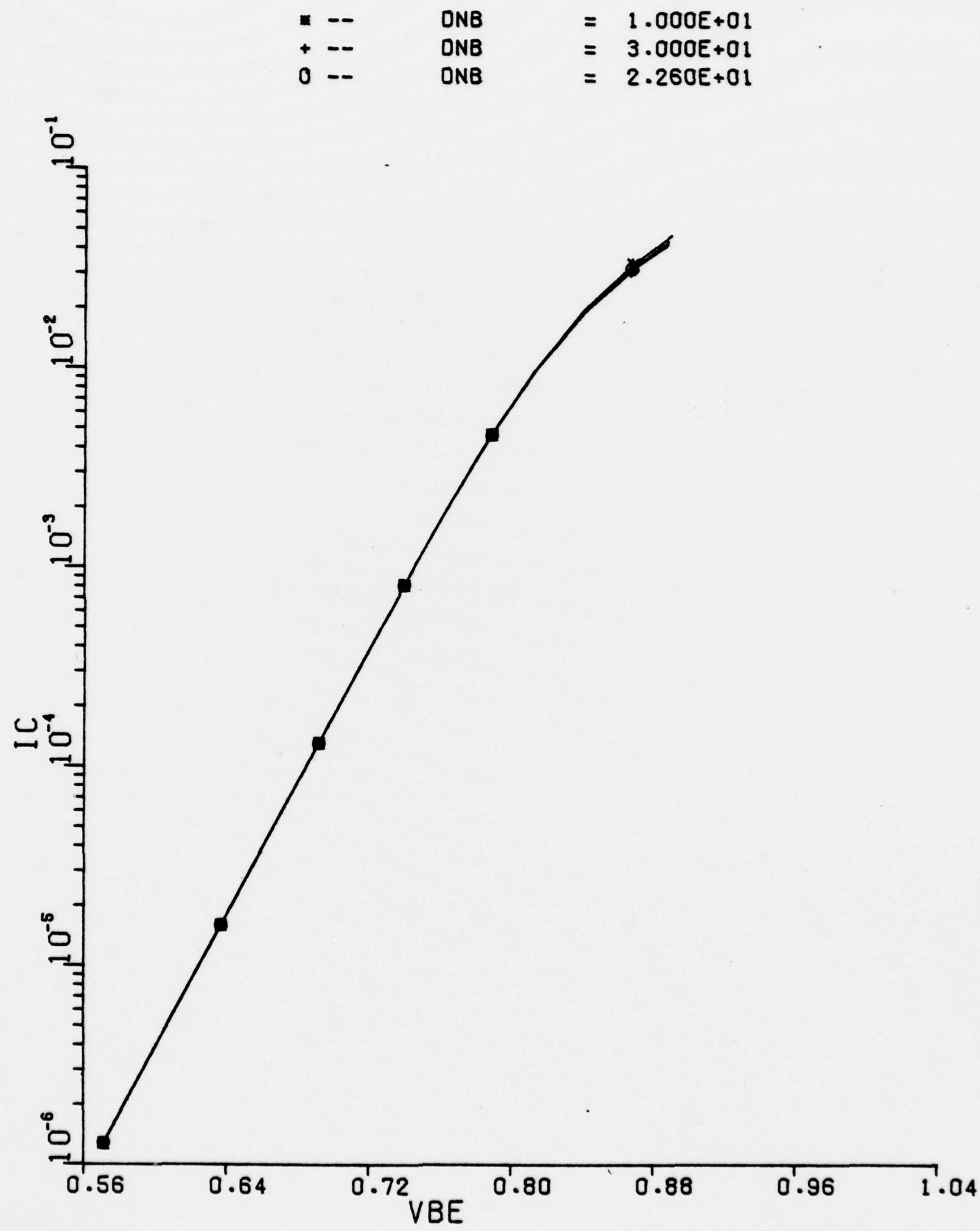

* -- W = 2.000E-05
+ -- W = 2.000E-04
O -- W = 6.000E-05
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.48
0.56
0.64
0.72
0.80
0.88
0.96
VBE



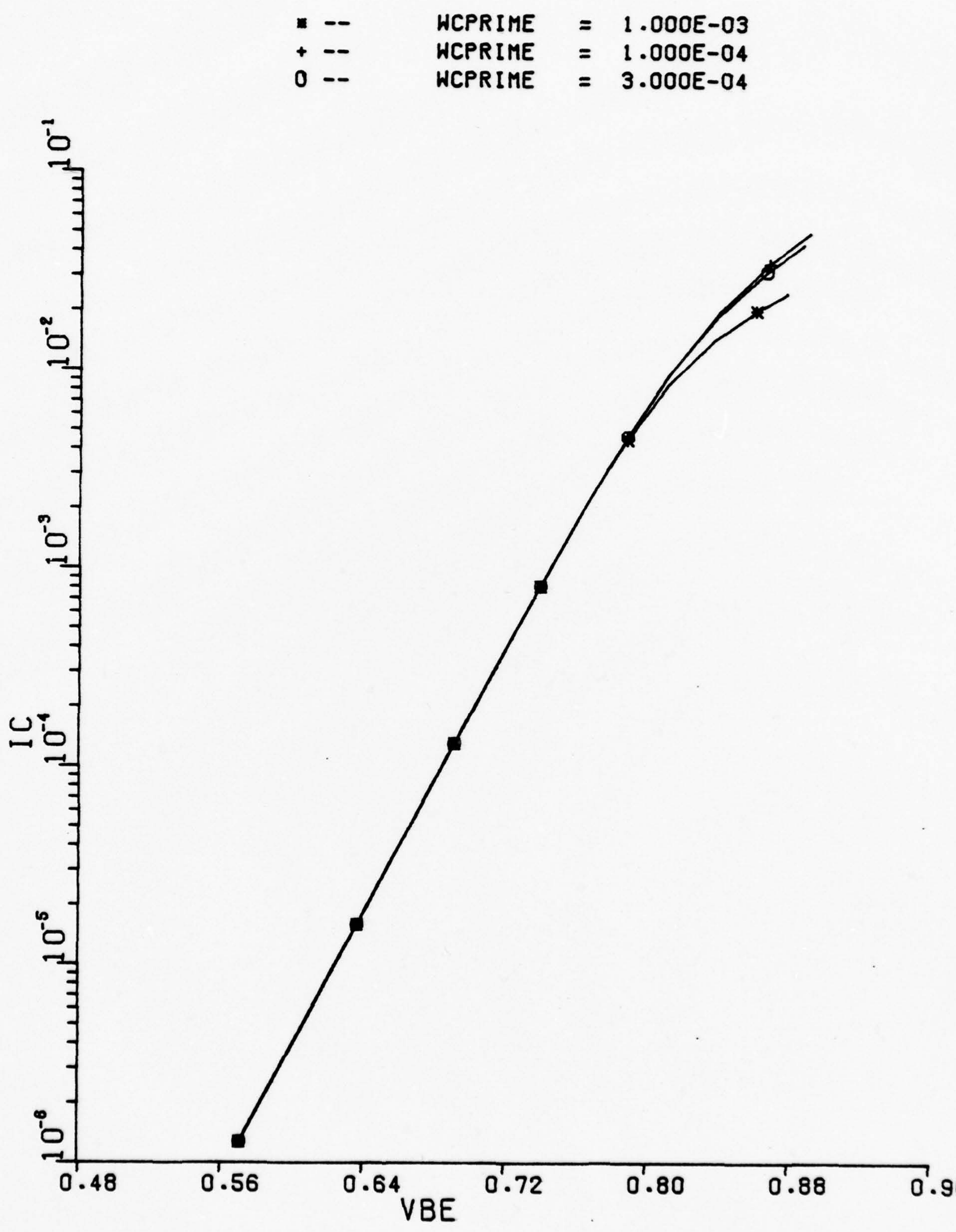
* -- AE = 1.000E-08
+ -- AE = 1.000E-04
O -- AE = 9.800E-07
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04



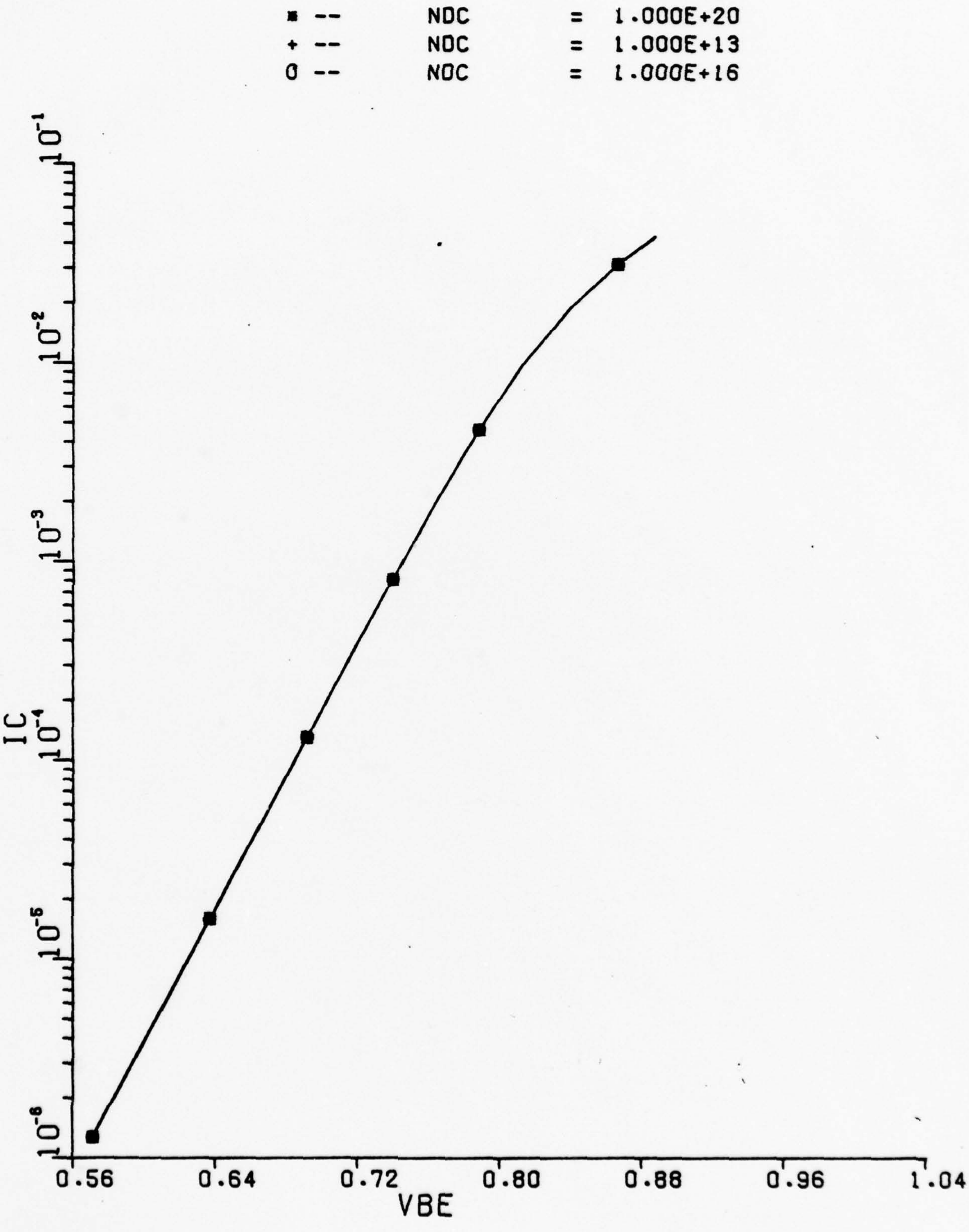
* -- VLIM = 1.000E+06
+ -- VLIM = 1.500E+07
0 -- VLIM = 6.000E+06
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04



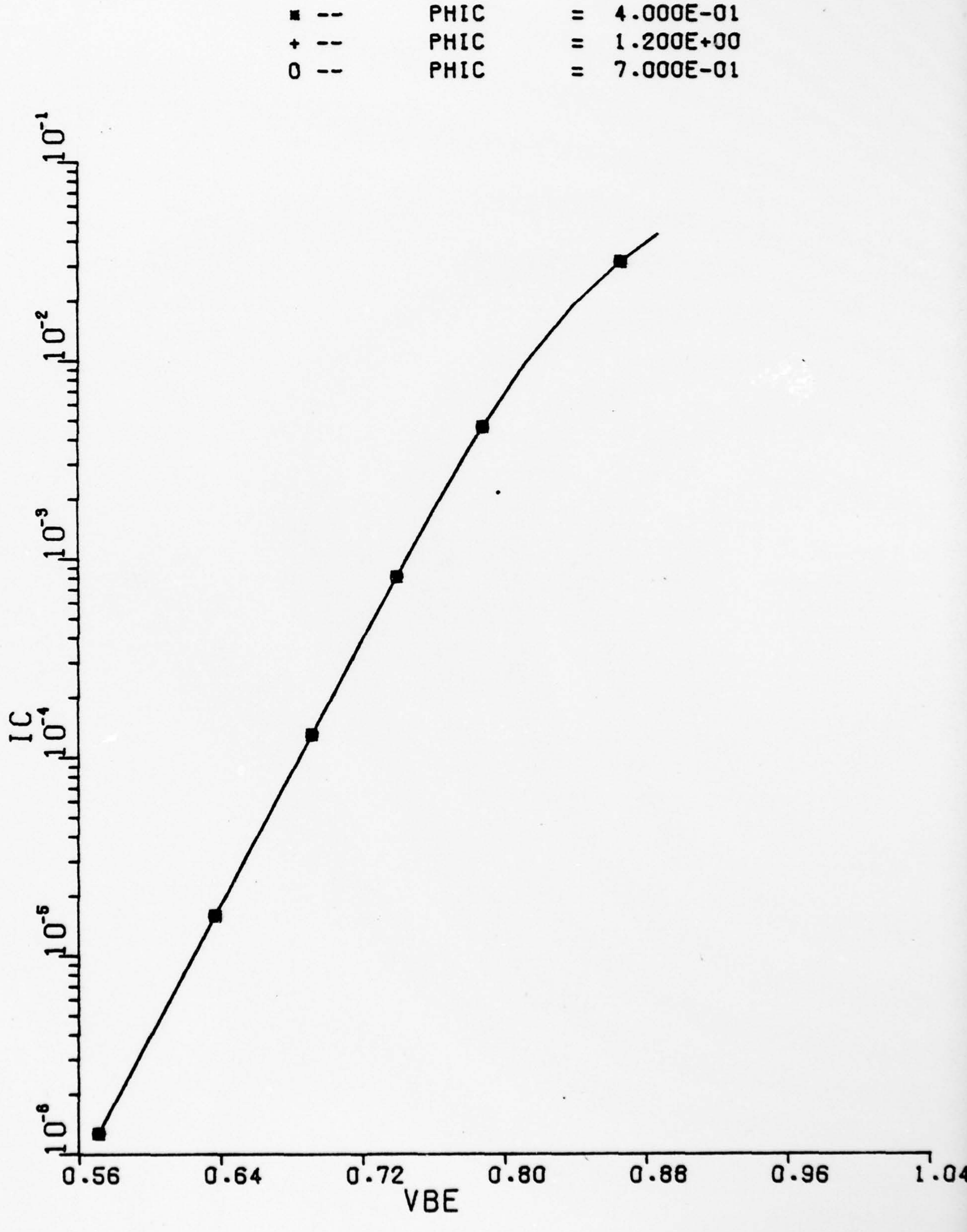
* -- DNB = 1.000E+01
+ -- DNB = 3.000E+01
0 -- DNB = 2.260E+01
IC
VBE
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04



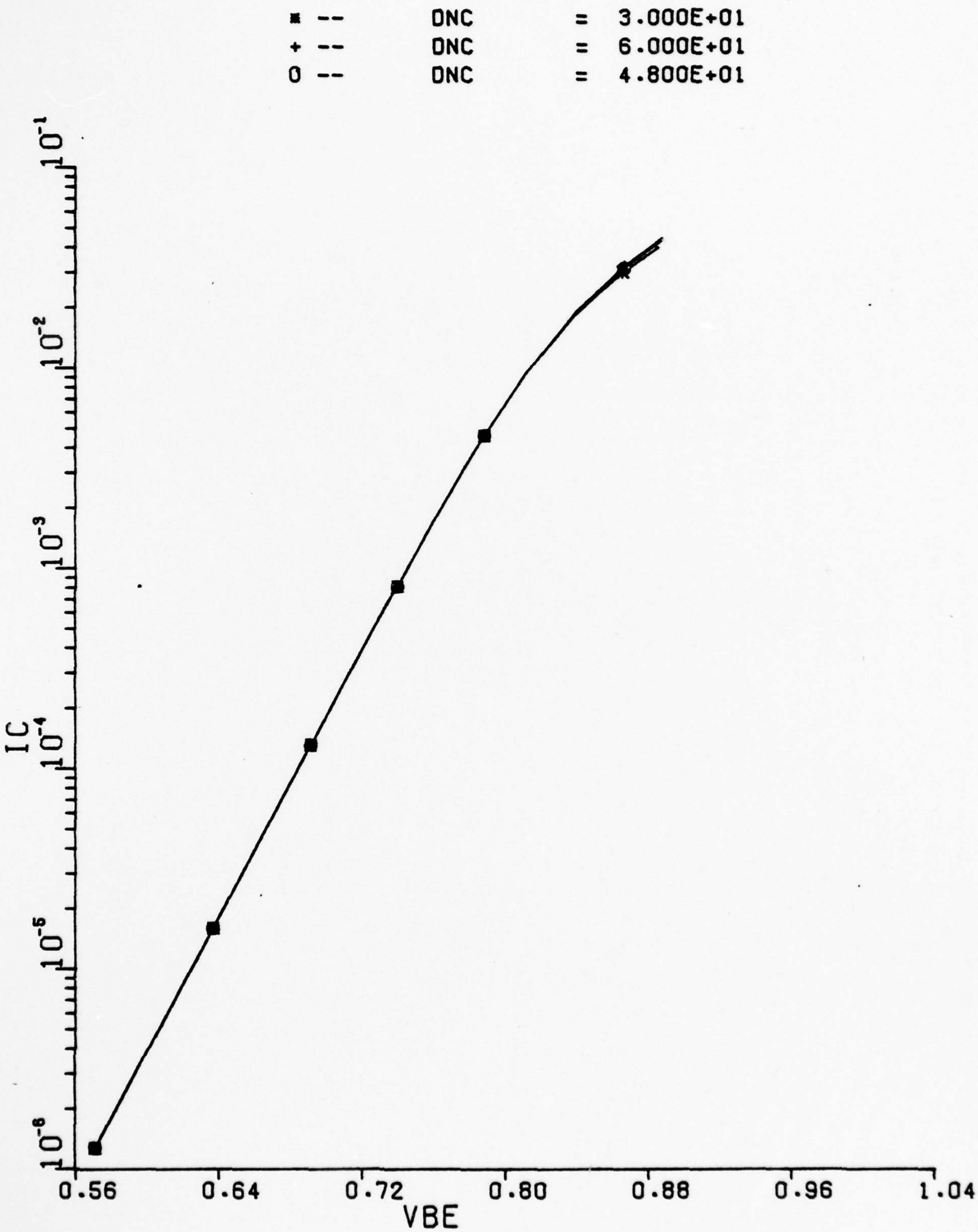
* -- WCPRIME = 1.000E-03
+ -- WCPRIME = 1.000E-04
O -- WCPRIME = 3.000E-04
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
IC
0.48
0.56
0.64
0.72
0.80
0.88
0.96
VBE



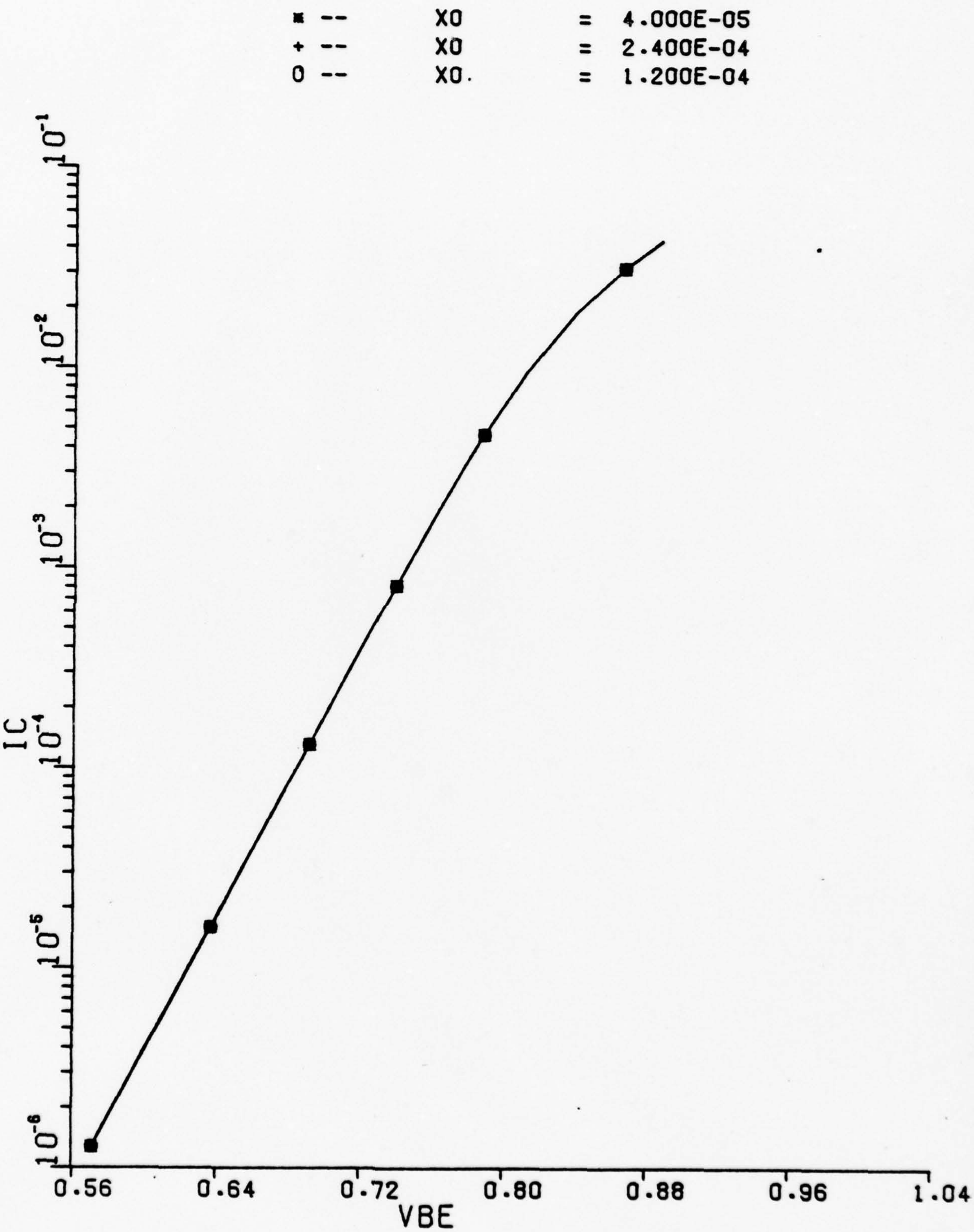
■ -- NDC = 1.000E+20
+ -- NDC = 1.000E+13
0 -- NDC = 1.000E+16
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE



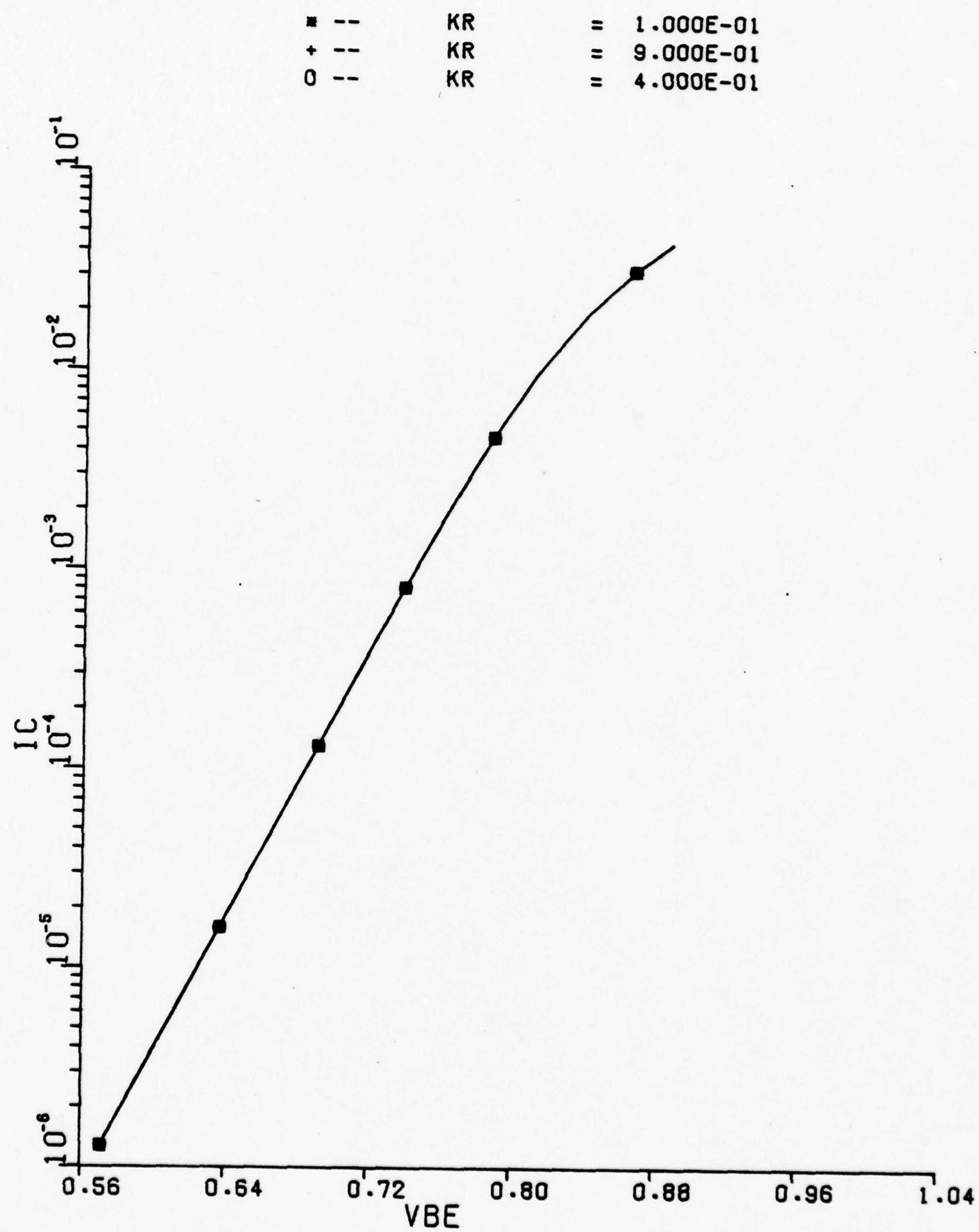
■ -- PHIC = 4.000E-01
+ -- PHIC = 1.200E+00
0 -- PHIC = 7.000E-01
IC
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

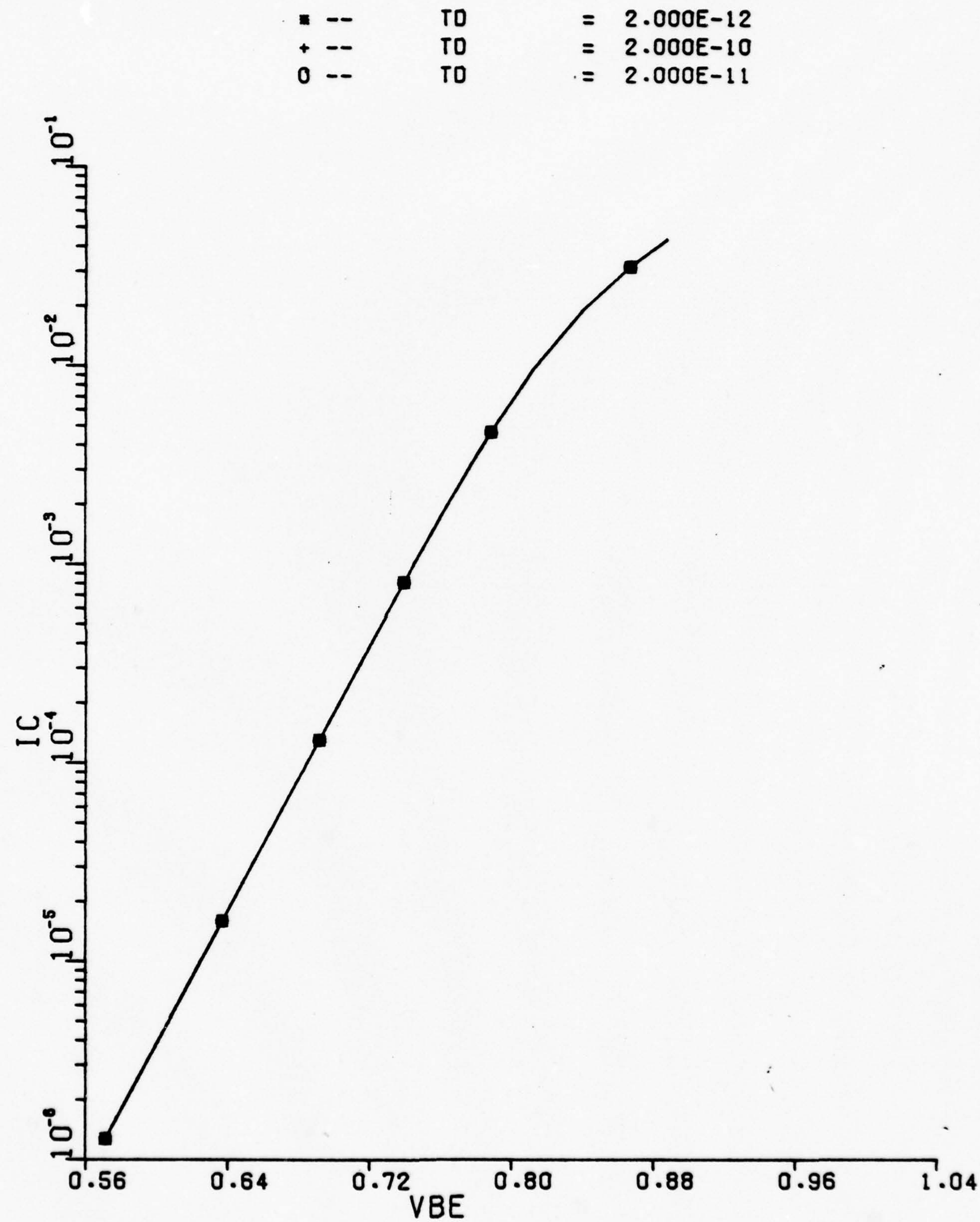


* -- DNC = 3.000E+01
+ -- DNC = 6.000E+01
0 -- DNC = 4.800E+01
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

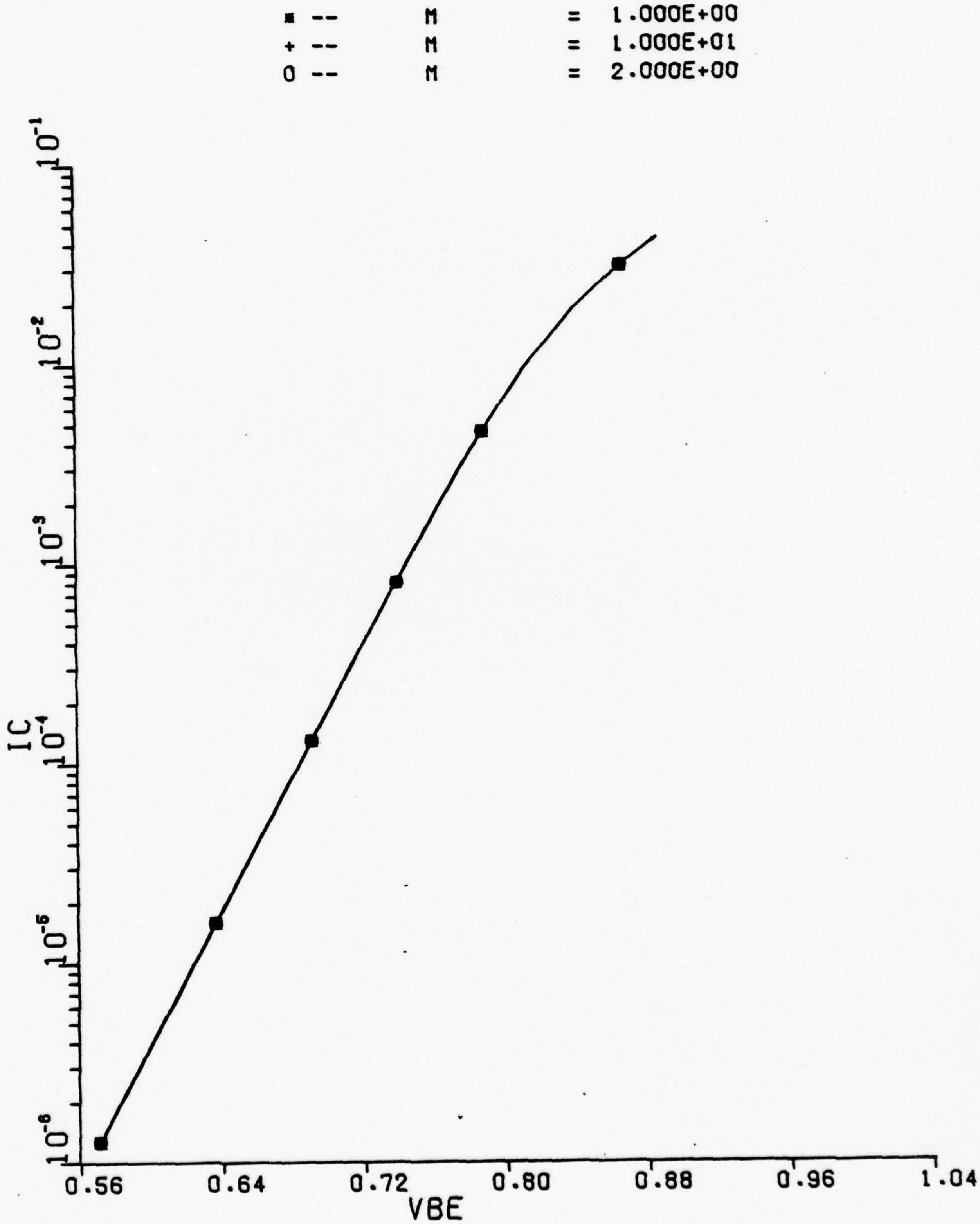


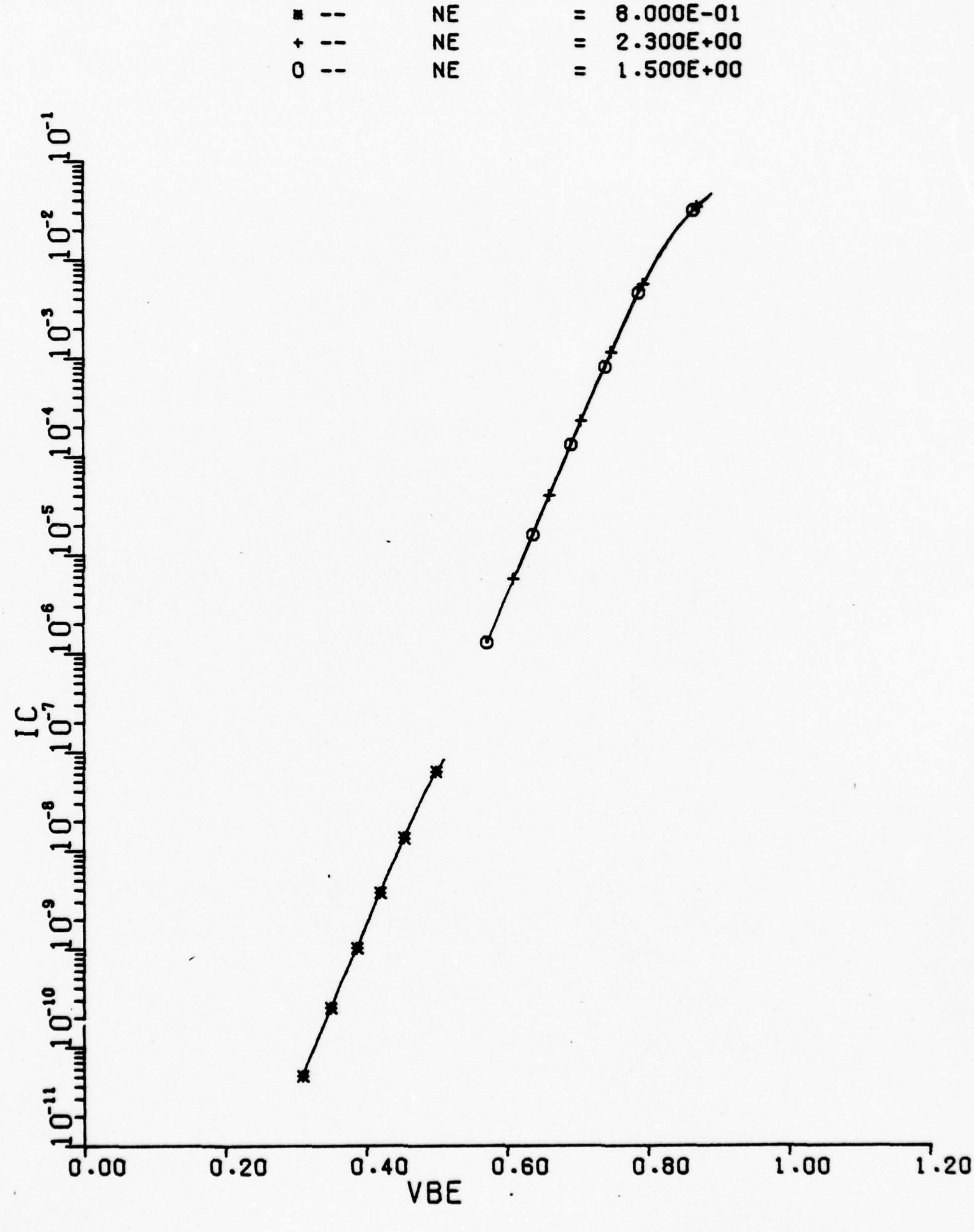
* -- XO = 4.000E-05
+ -- XO = 2.400E-04
O -- XO. = 1.200E-04
IC
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE


* -- KR = 1.000E-01
+ -- KR = 9.000E-01
0 -- KR = 4.000E-01
IC
VBE
0.56
0.64
0.72
0.80
0.88
0.96
1.04

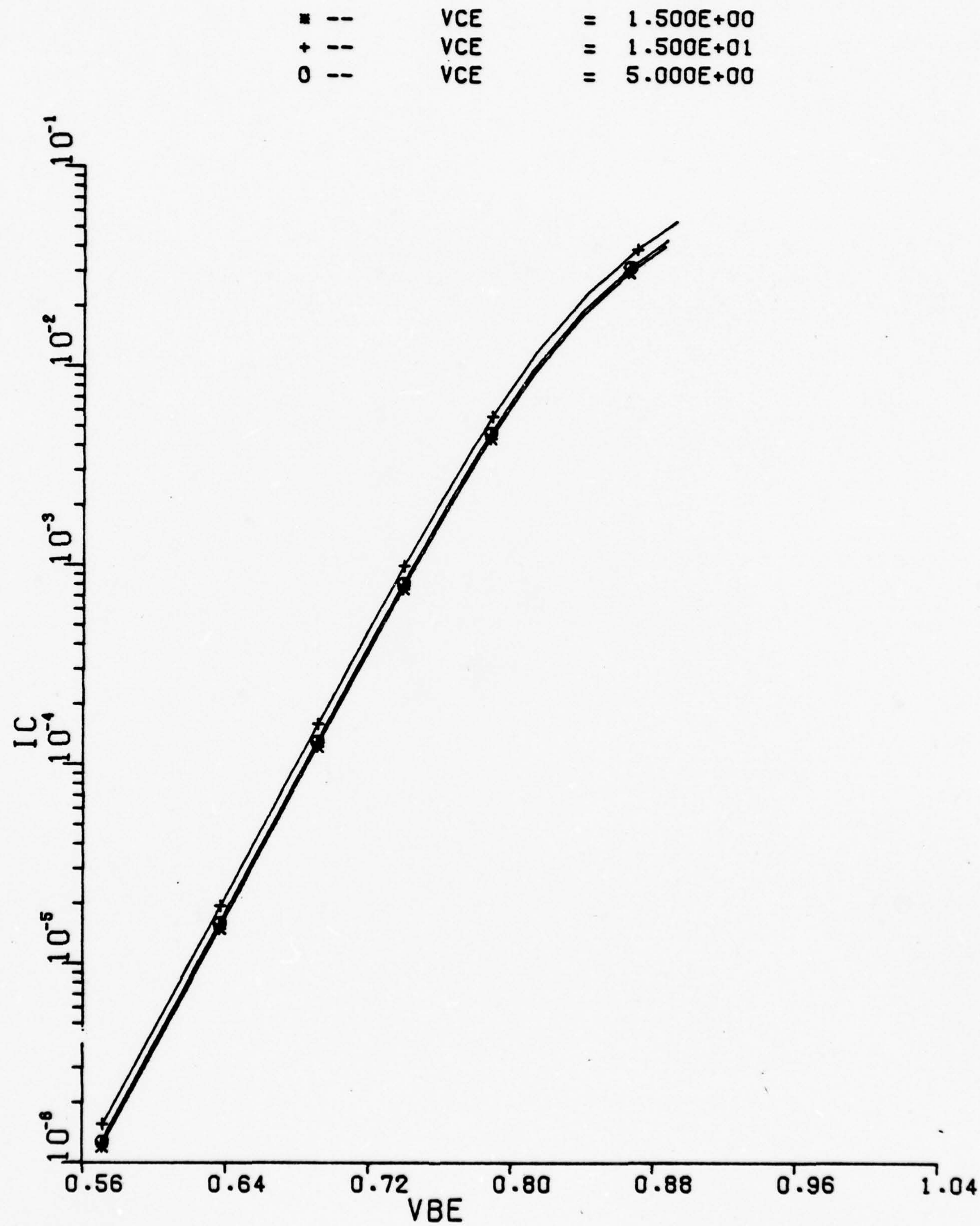


■ -- TD = 2.000E-12
+ -- TD = 2.000E-10
O -- TD = 2.000E-11
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
IC
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

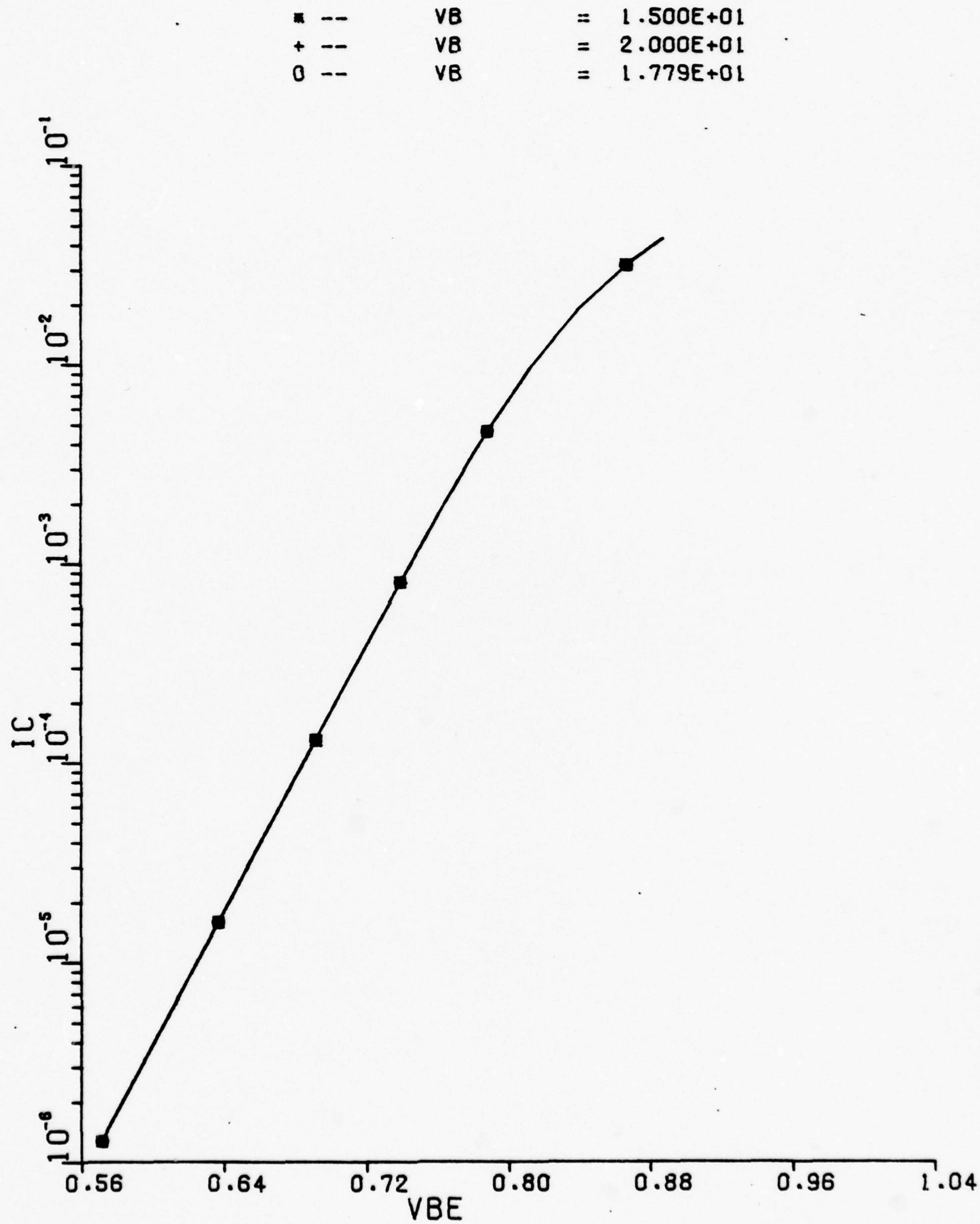

* -- M = 1.000E+00
+ -- M = 1.000E+01
0 -- M = 2.000E+00
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

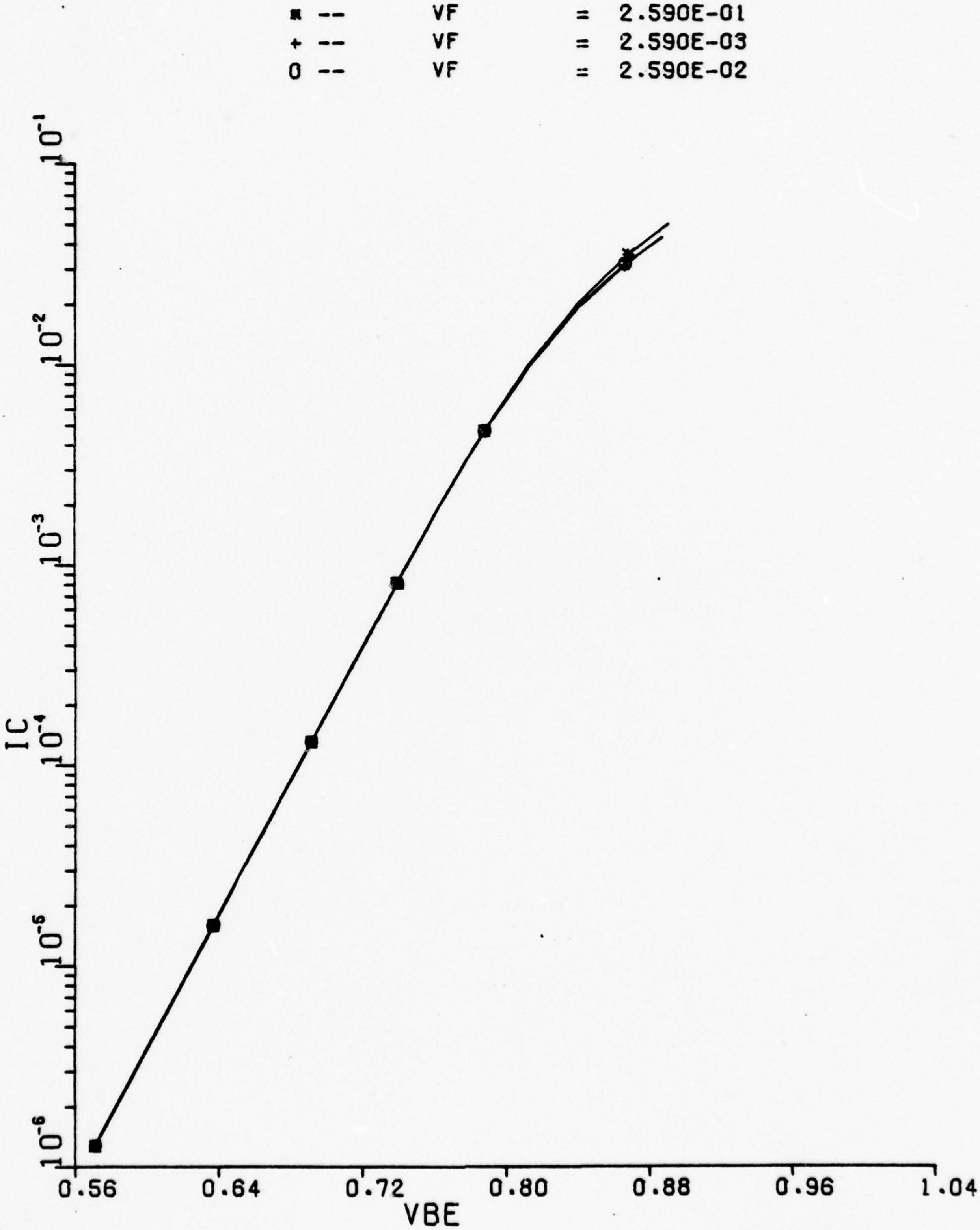


* -- NE = 8.000E-01
+ -- NE = 2.300E+00
0 -- NE = 1.500E+00
IC
VBE
0.00
0.20
0.40
0.60
0.80
1.00
1.20

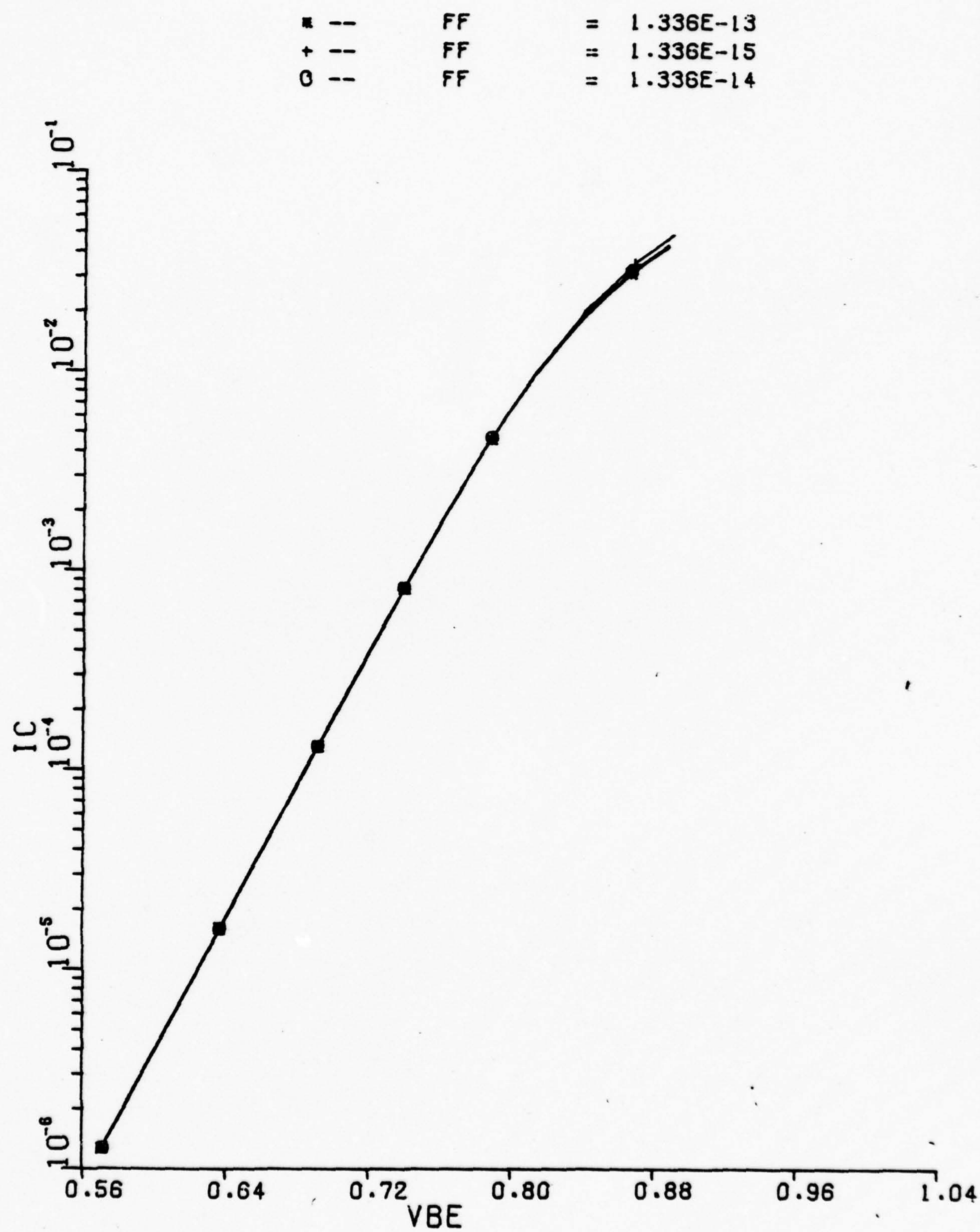


* -- VCE = 1.500E+00
+ -- VCE = 1.500E+01
0 -- VCE = 5.000E+00
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE


* -- VB = 1.500E+01
+ -- VB = 2.000E+01
0 -- VB = 1.779E+01
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

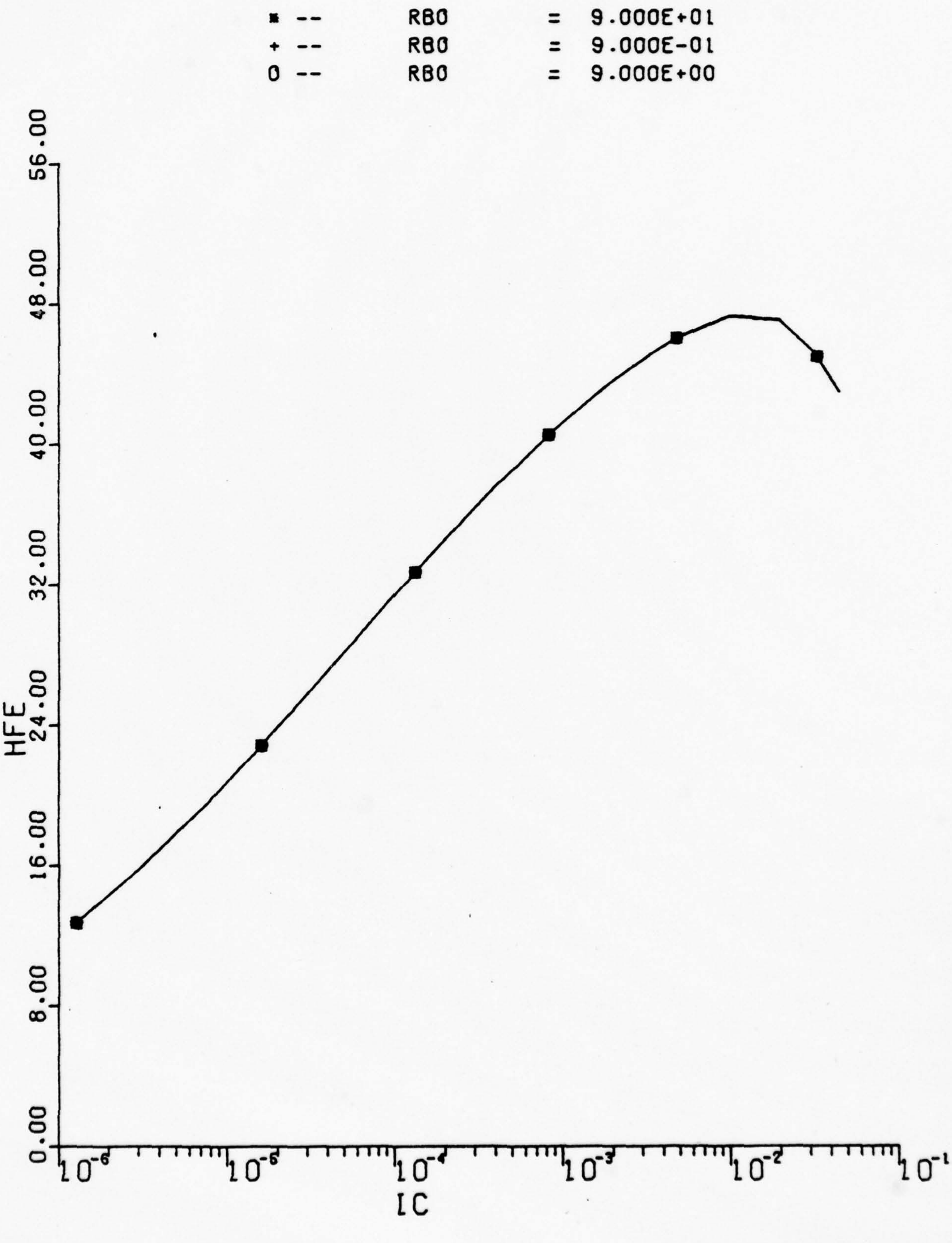


* -- VF = 2.590E-01
+ -- VF = 2.590E-03
O -- VF = 2.590E-02
IC
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

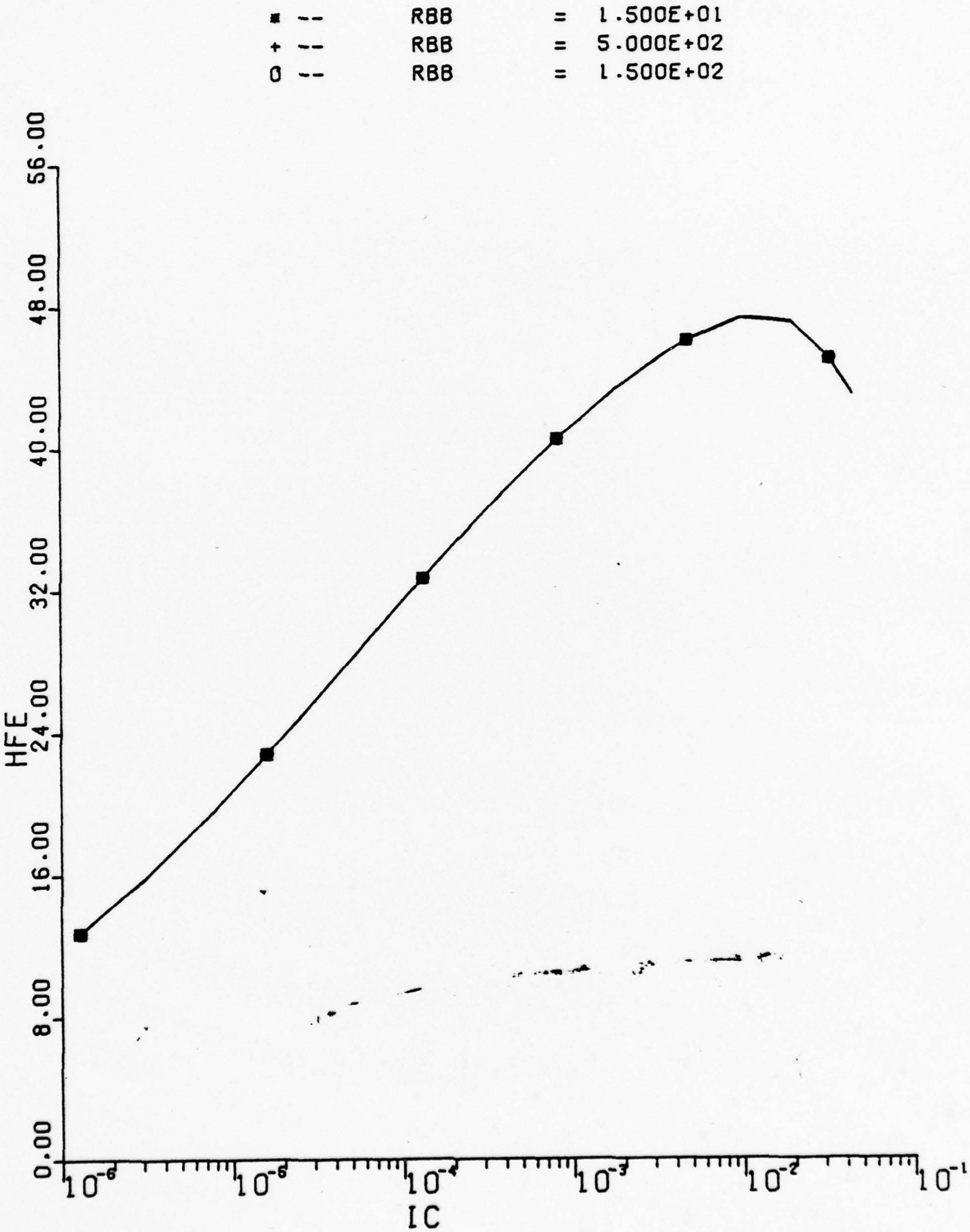


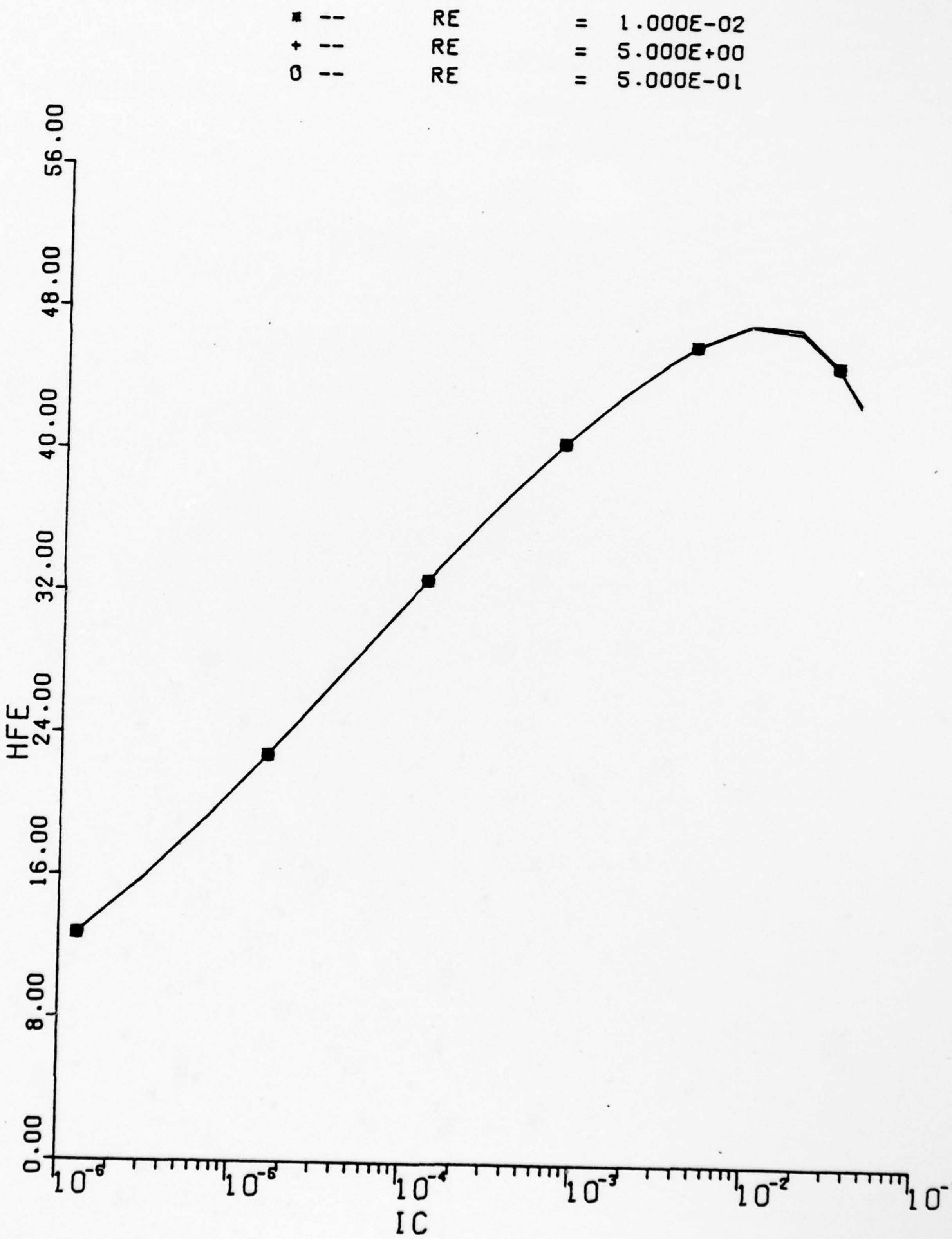
* -- FF = 1.336E-13
+ -- FF = 1.336E-15
O -- FF = 1.336E-14
IC
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
0.56
0.64
0.72
0.80
0.88
0.96
1.04
VBE

B.3 HFE vs. $I_C$ Curves

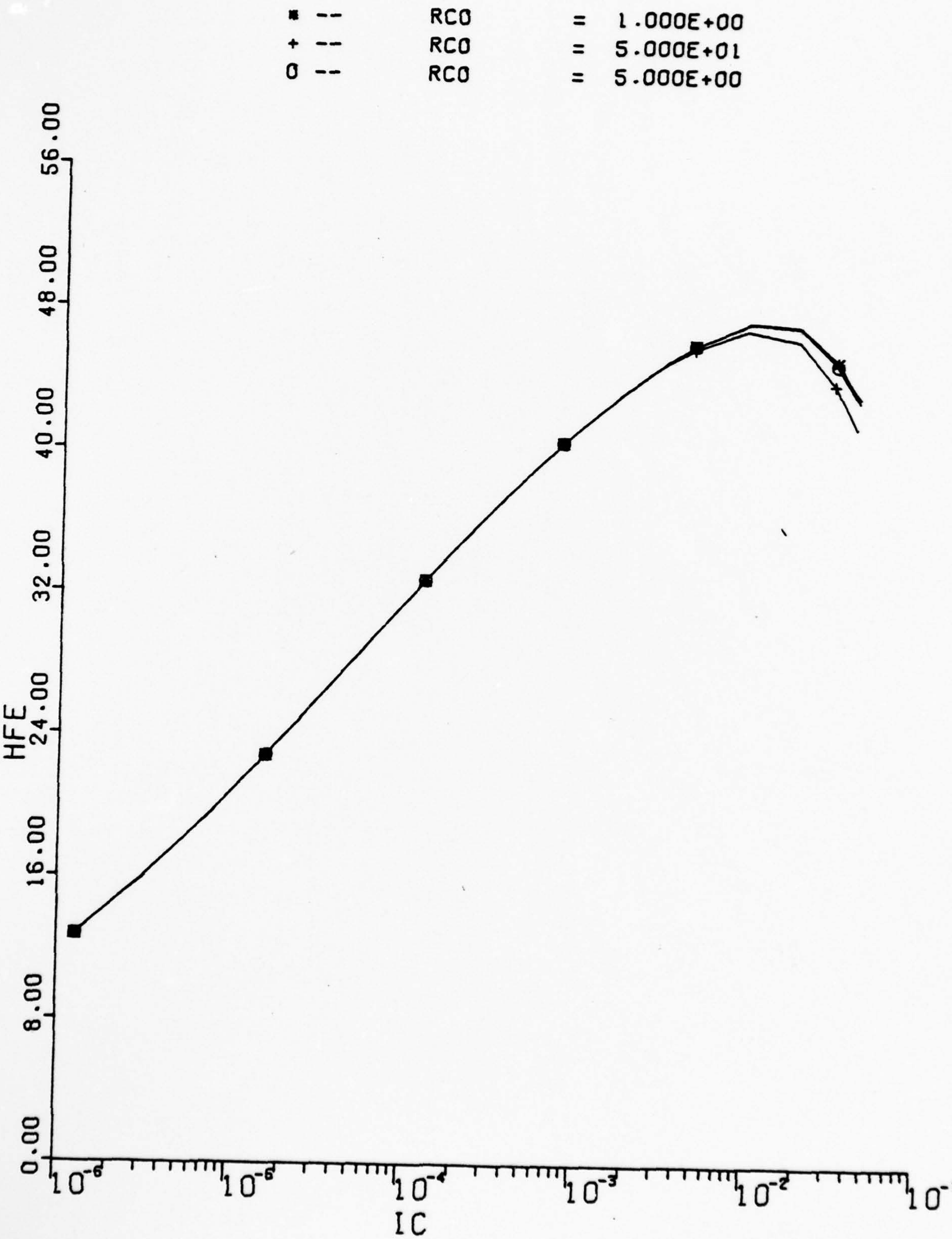


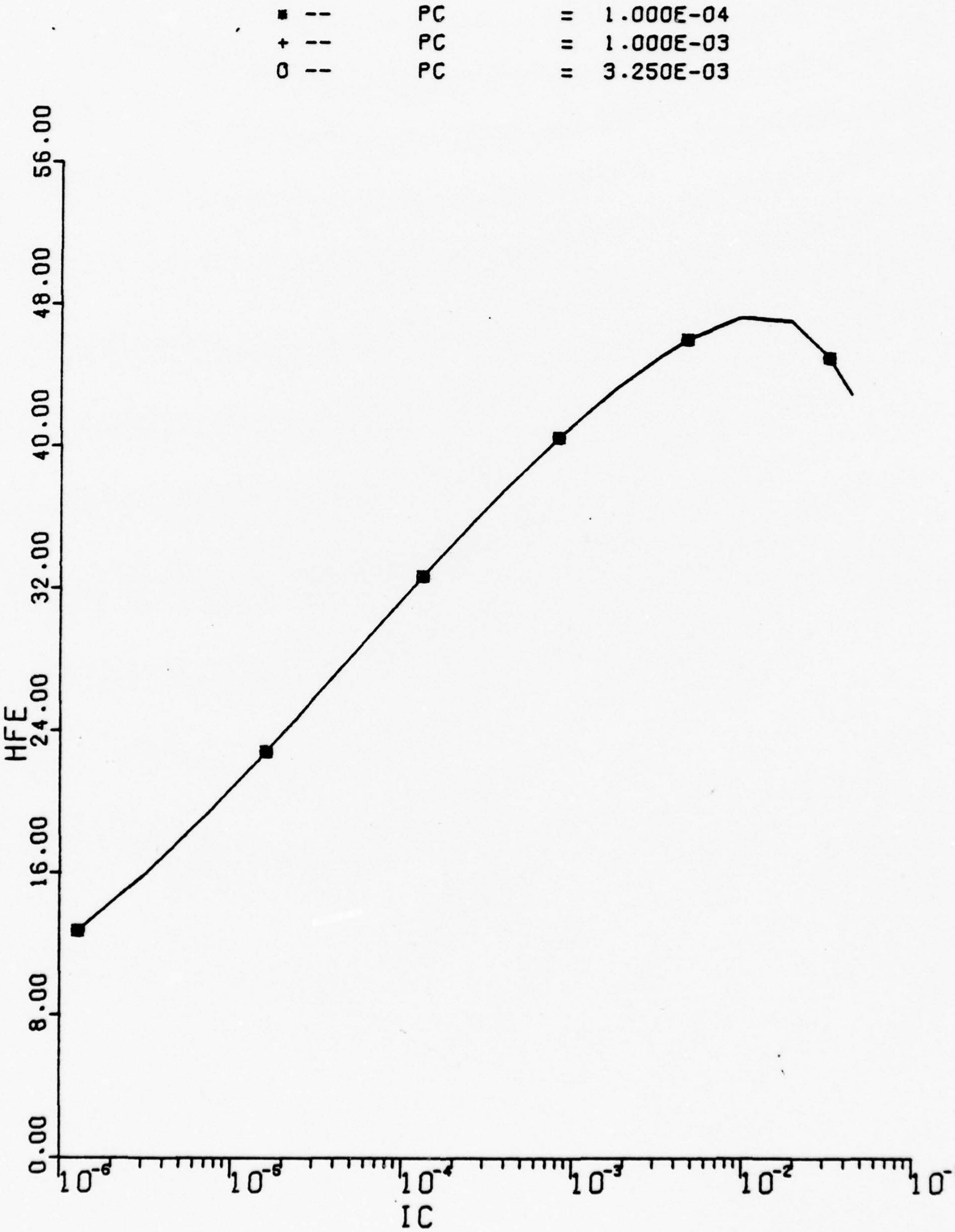
* -- RBO = 9.000E+01
+ -- RBO = 9.000E-01
0 -- RBO = 9.000E+00
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
HFE
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
IC


* -- RBB = 1.500E+01
+ -- RBB = 5.000E+02
0 -- RBB = 1.500E+02
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
HFE
IC

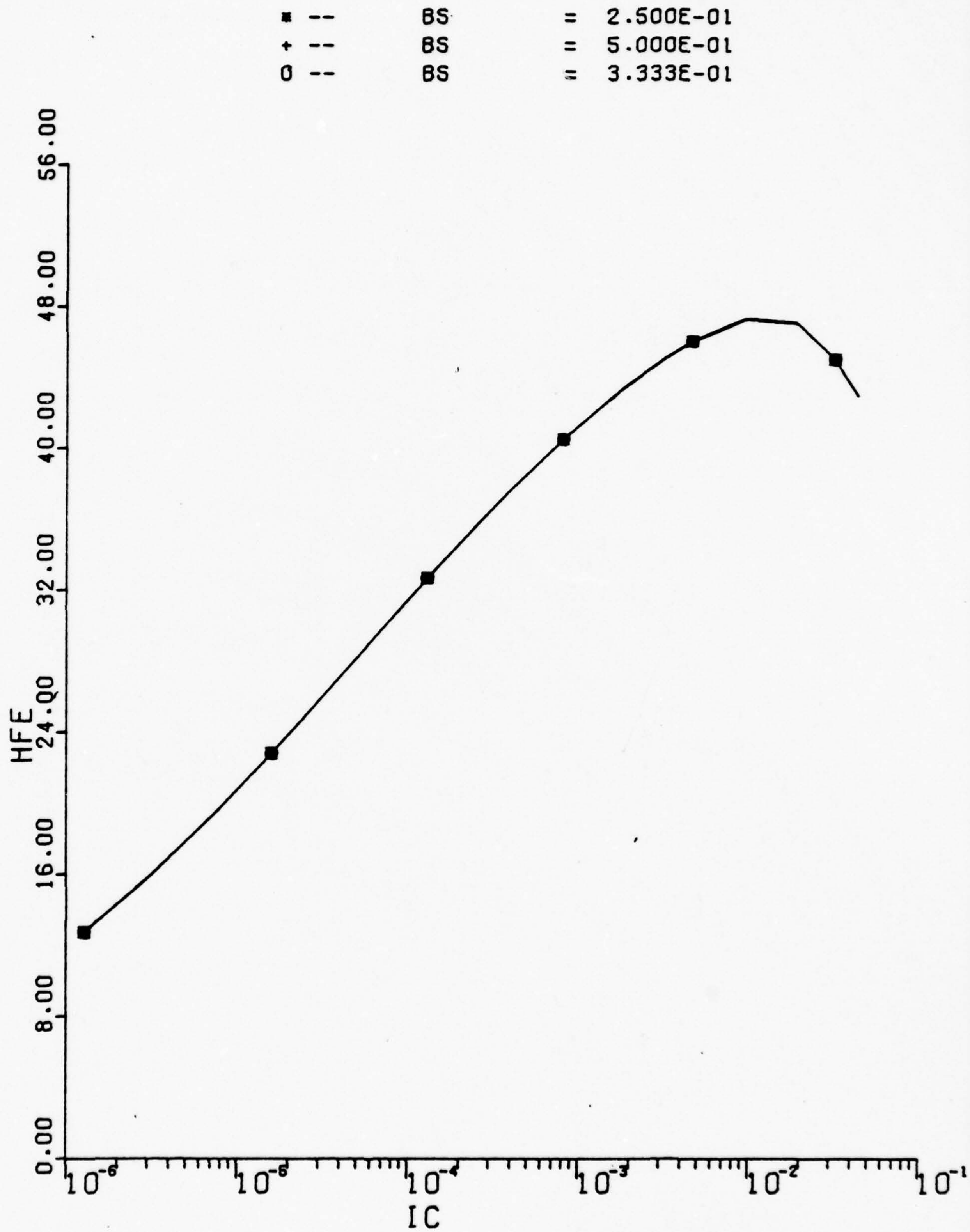


■ -- RE = 1.000E-02
+ -- RE = 5.000E+00
O -- RE = 5.000E-01
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
HFE
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC

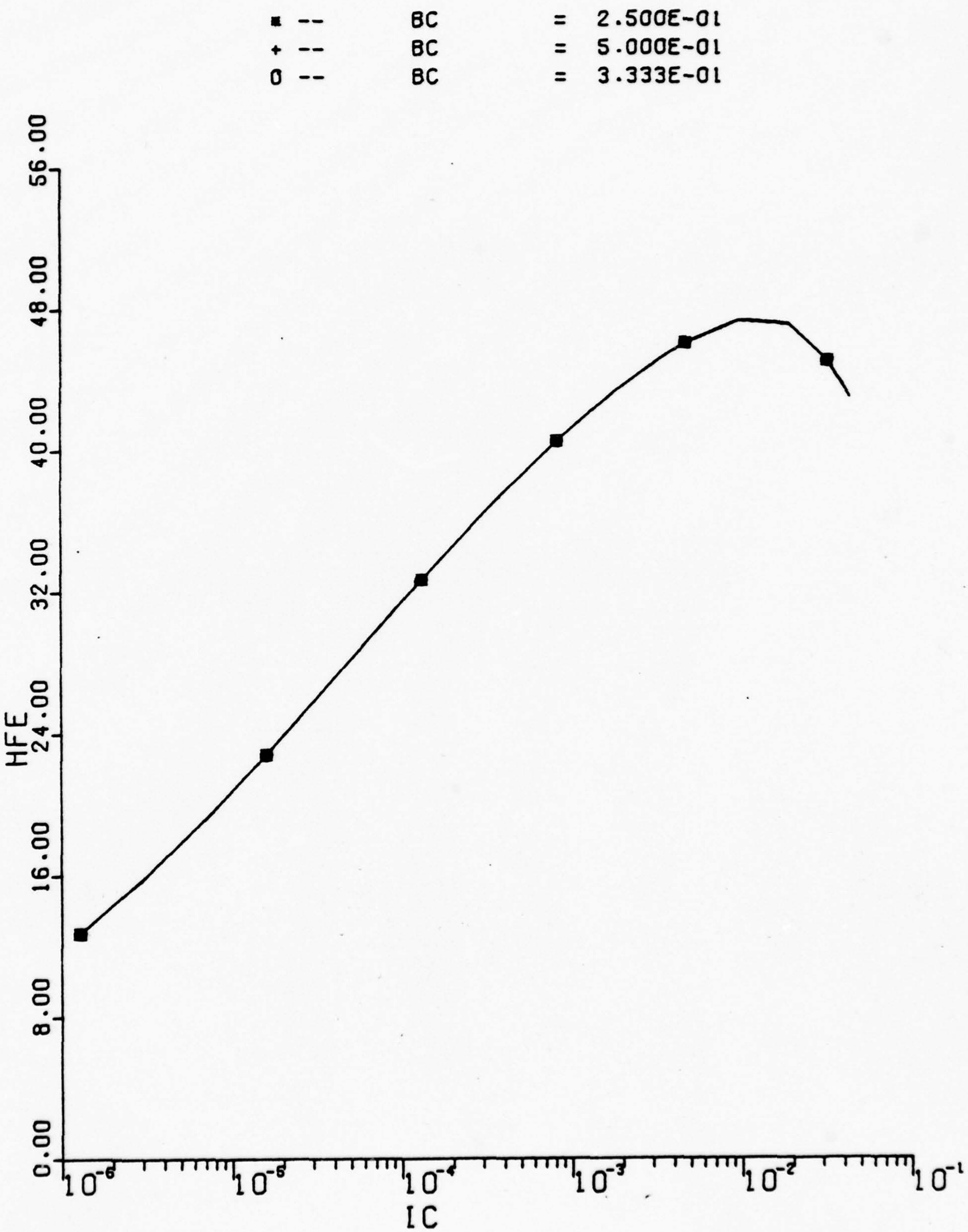

* -- RCO = 1.000E+00
+ -- RCO = 5.000E+01
O -- RCO = 5.000E+00
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$



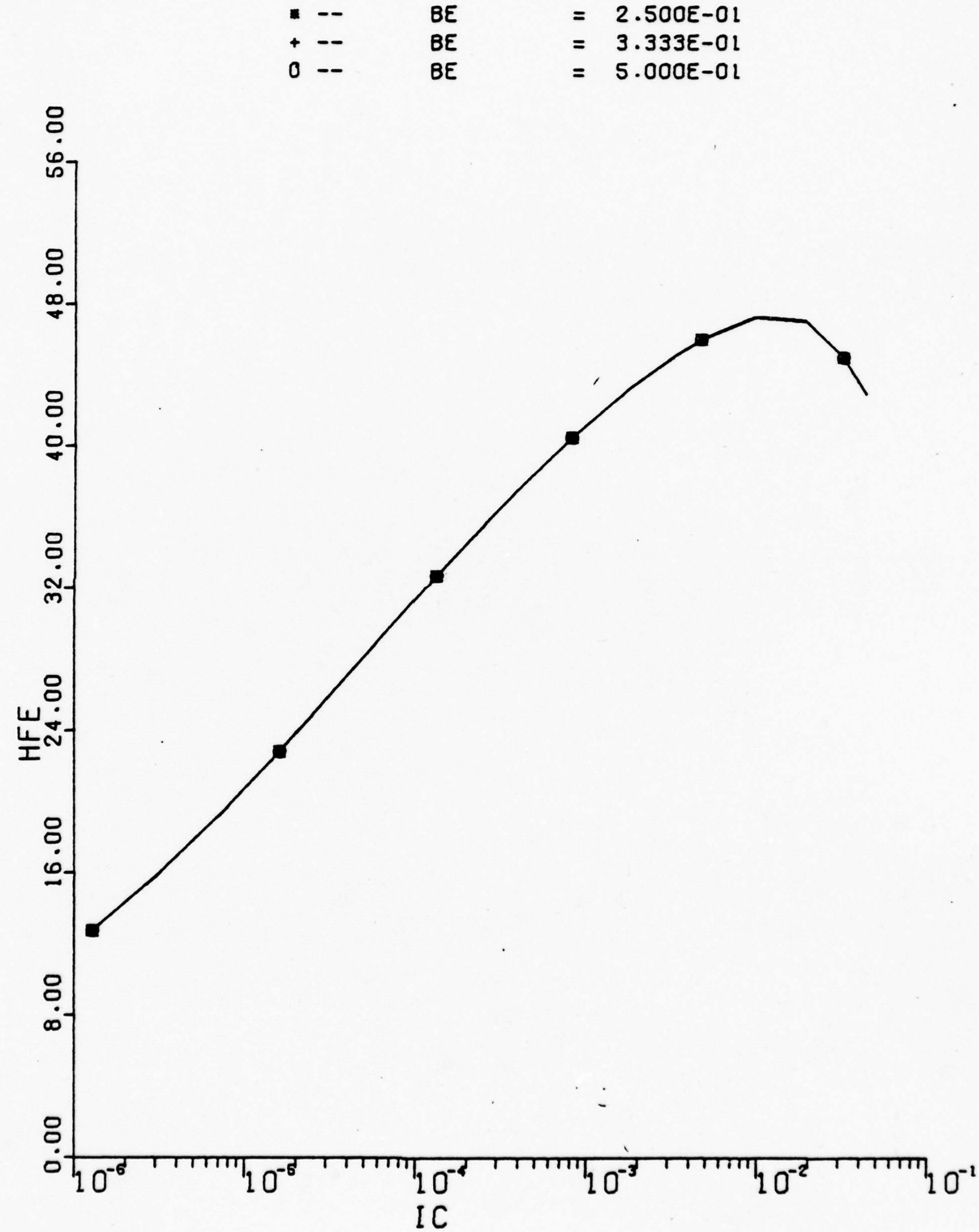
■ -- PC = 1.000E-04
+ -- PC = 1.000E-03
0 -- PC = 3.250E-03
HFE
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$



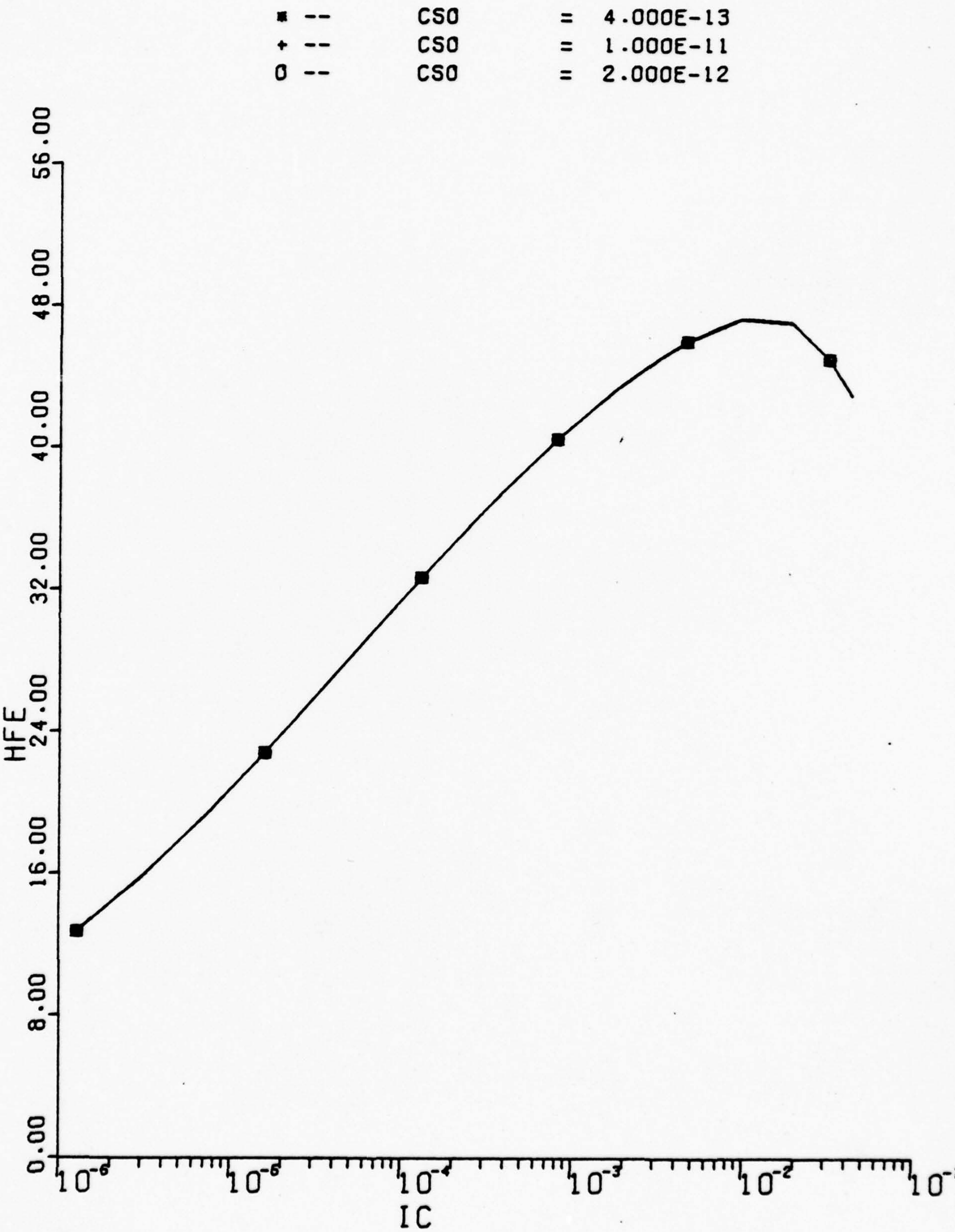
■ -- BS = 2.500E-01
+ -- BS = 5.000E-01
O -- BS = 3.333E-01
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
HFE
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC

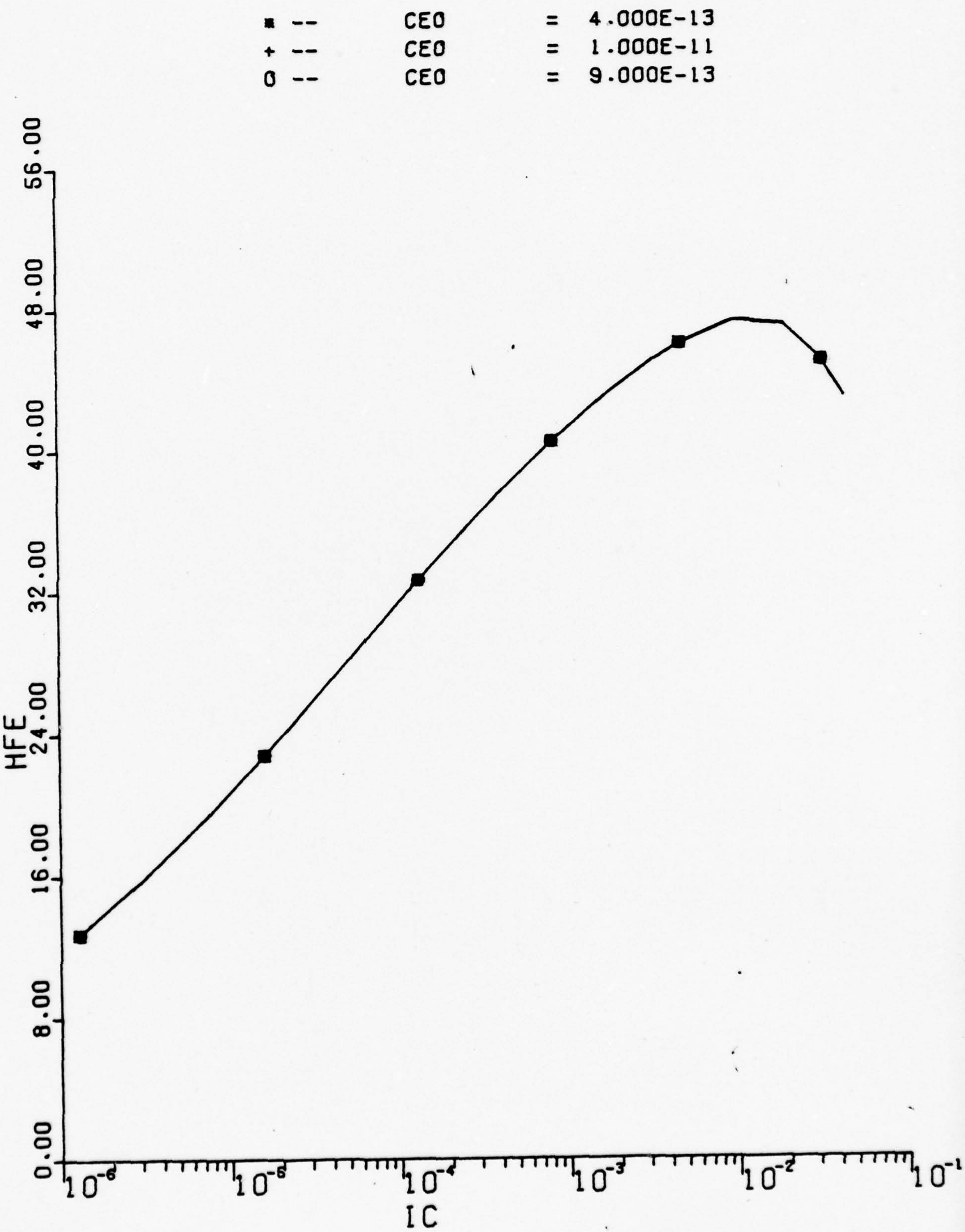


▪ -- BC = 2.500E-01
+ -- BC = 5.000E-01
0 -- BC = 3.333E-01
HFE
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
IC
10-6
10-5
10-4
10-3
10-2
10-1

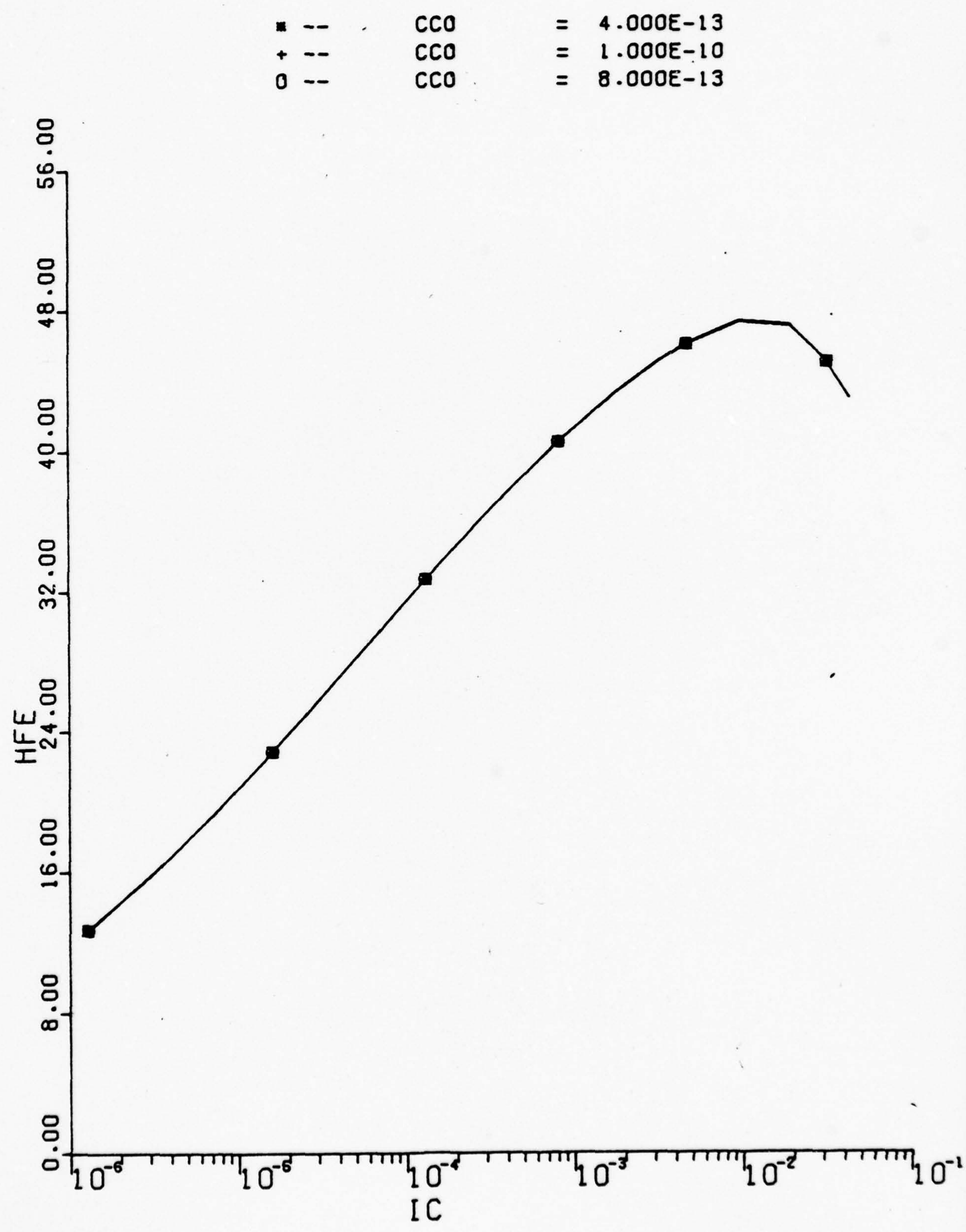


■ -- BE = 2.500E-01
+ -- BE = 3.333E-01
O -- BE = 5.000E-01
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1
IC

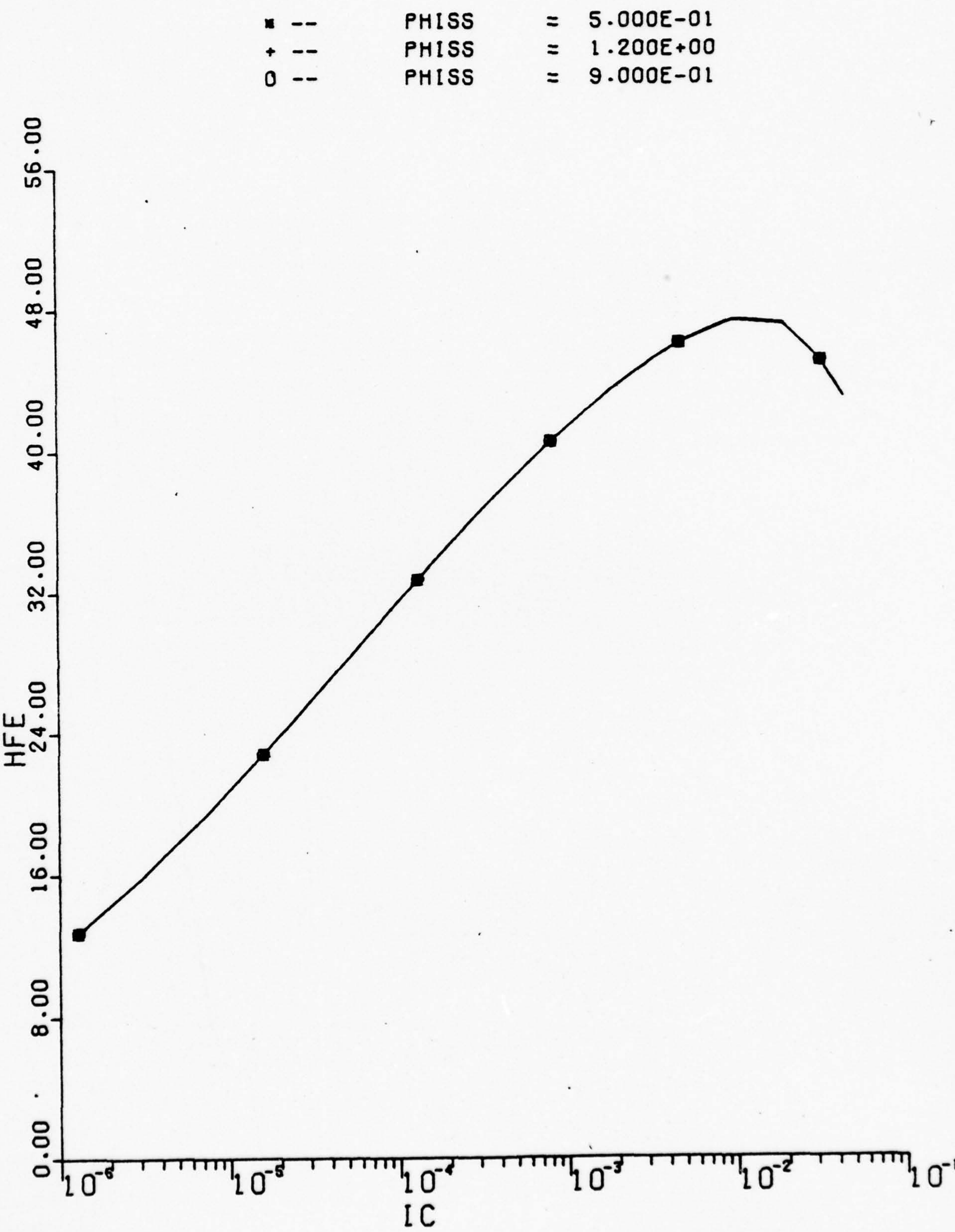

* -- CSO = 4.000E-13
+ -- CSO = 1.000E-11
O -- CSO = 2.000E-12
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
IC



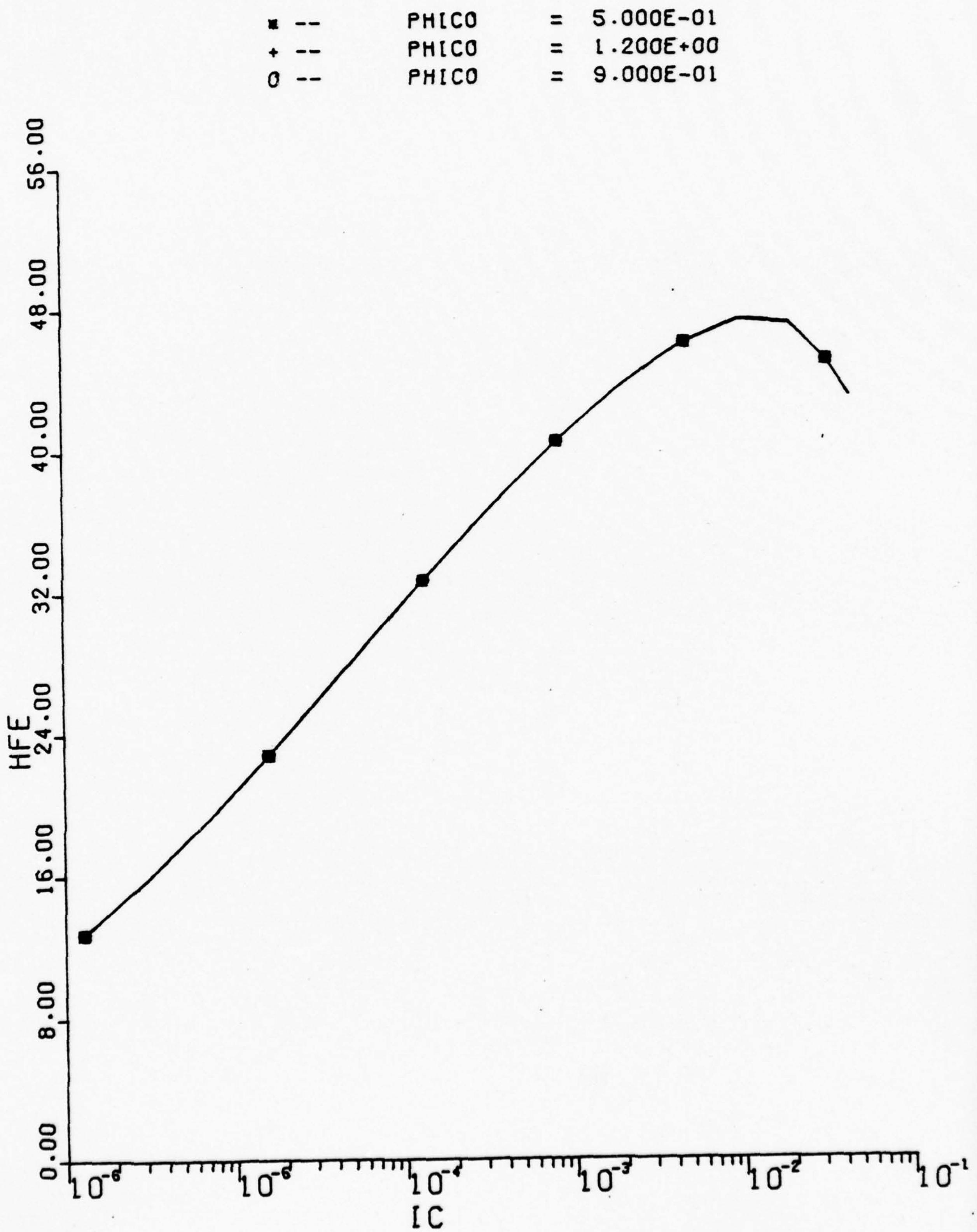
* -- CEO = 4.000E-13
+ -- CEO = 1.000E-11
O -- CEO = 9.000E-13
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
IC
10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹



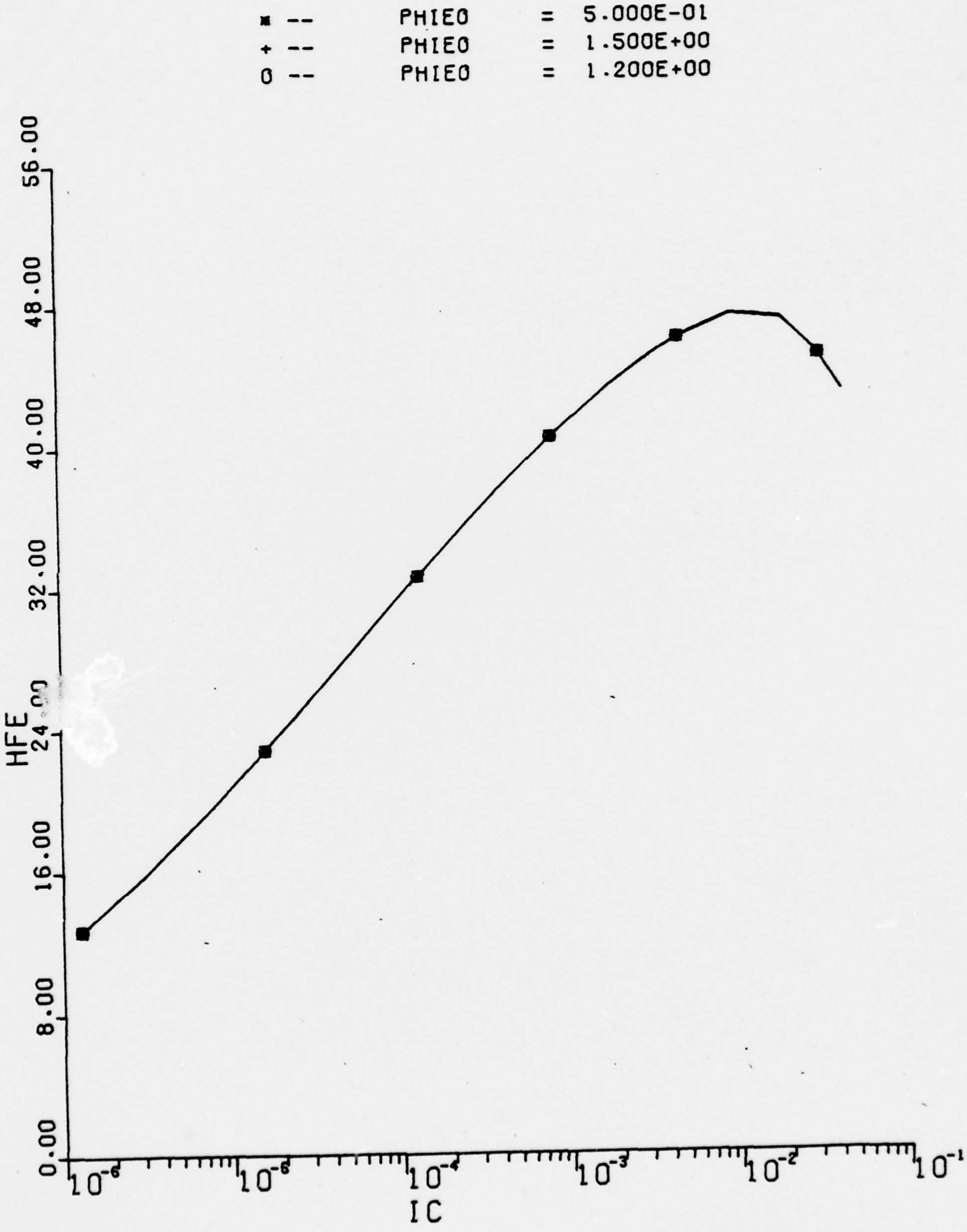
■ -- CCO = 4.000E-13
+ -- CCO = 1.000E-10
0 -- CCO = 8.000E-13
56.00
48.00
40.00
32.00
24.00
HFE
16.00
8.00
0.00
10⁻⁶
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
IC



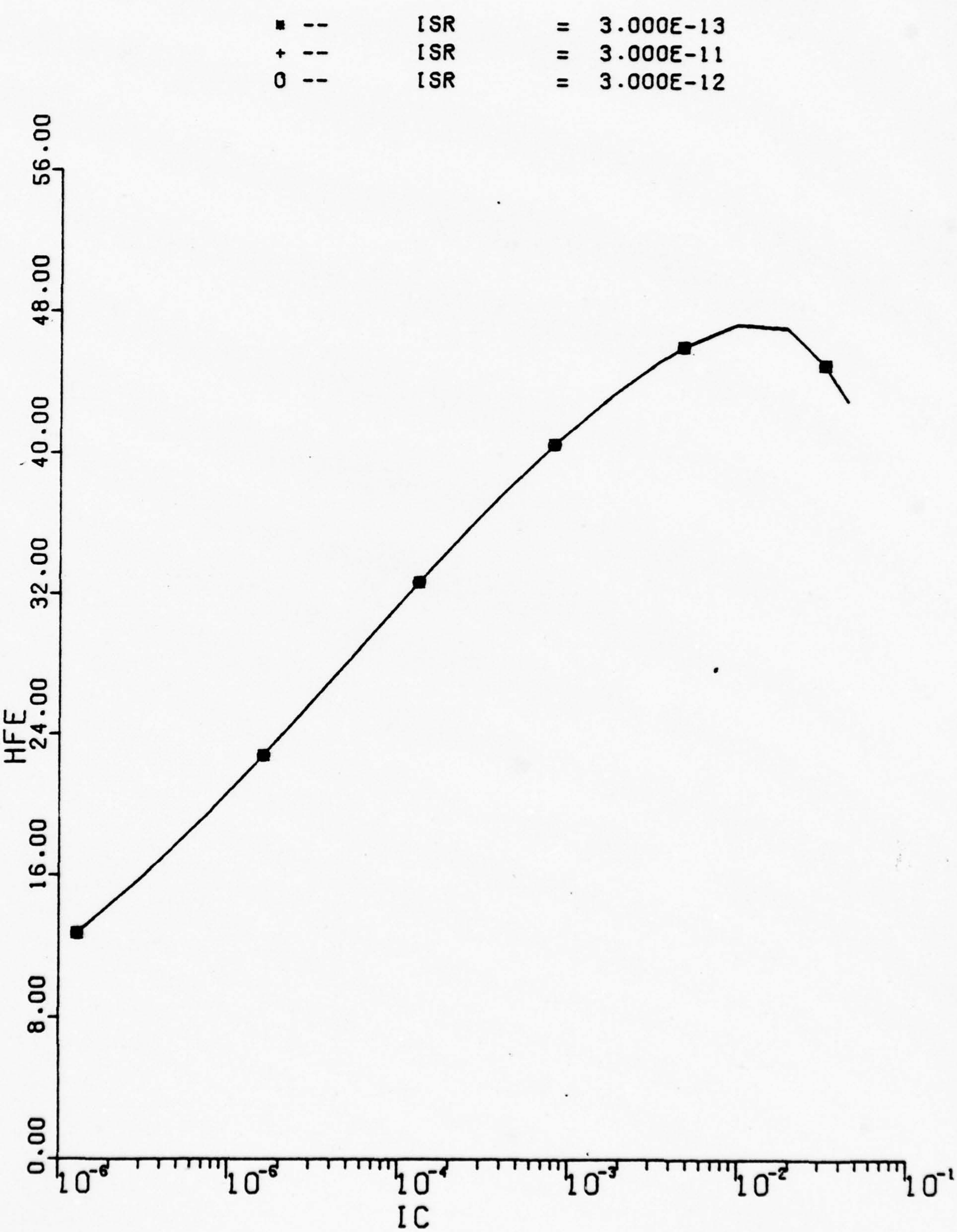
* -- PHISS = 5.000E-01
+ -- PHISS = 1.200E+00
0 -- PHISS = 9.000E-01
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
HFE
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC



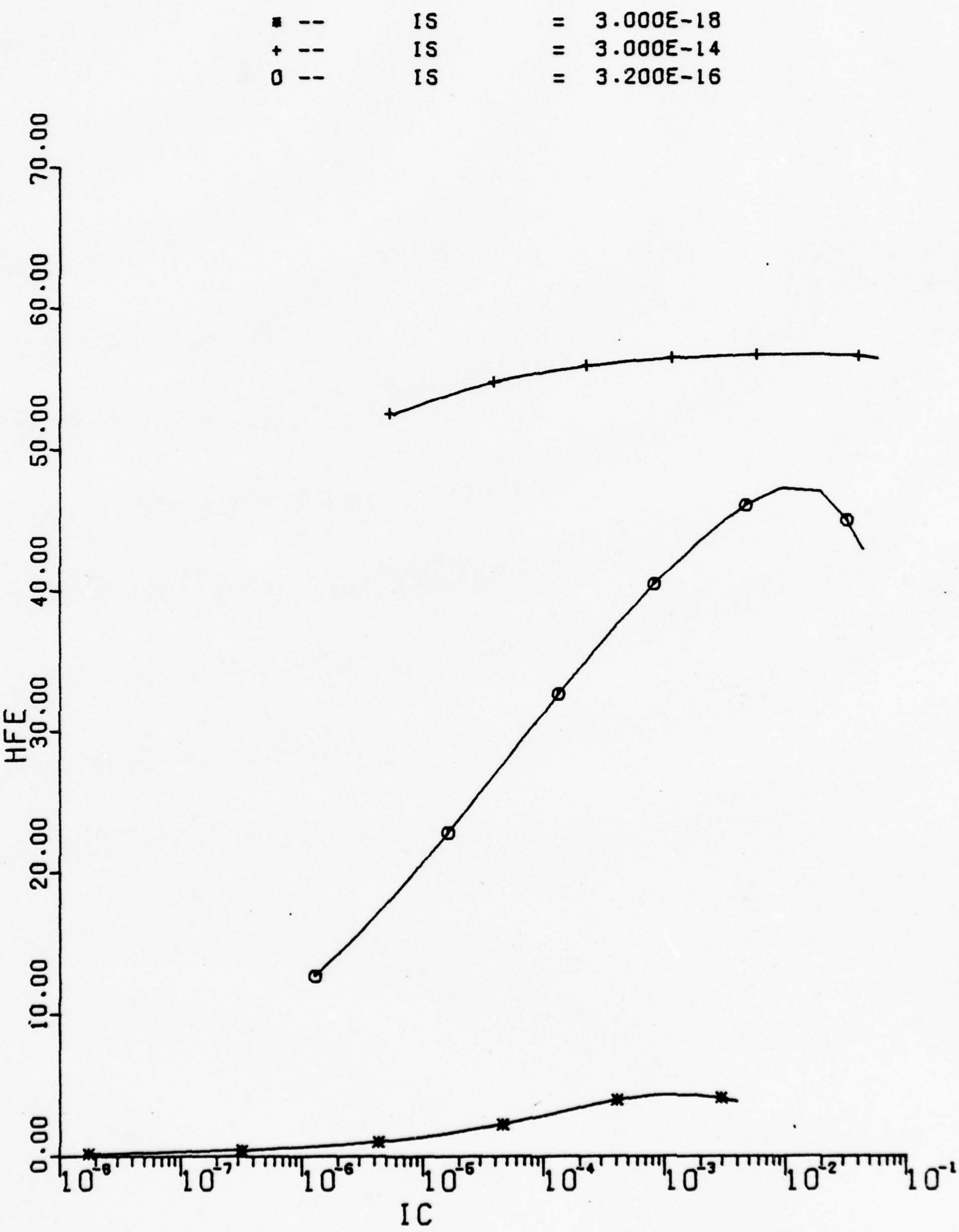
* -- PHICO = 5.000E-01
+ -- PHICO = 1.200E+00
O -- PHICO = 9.000E-01
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
IC

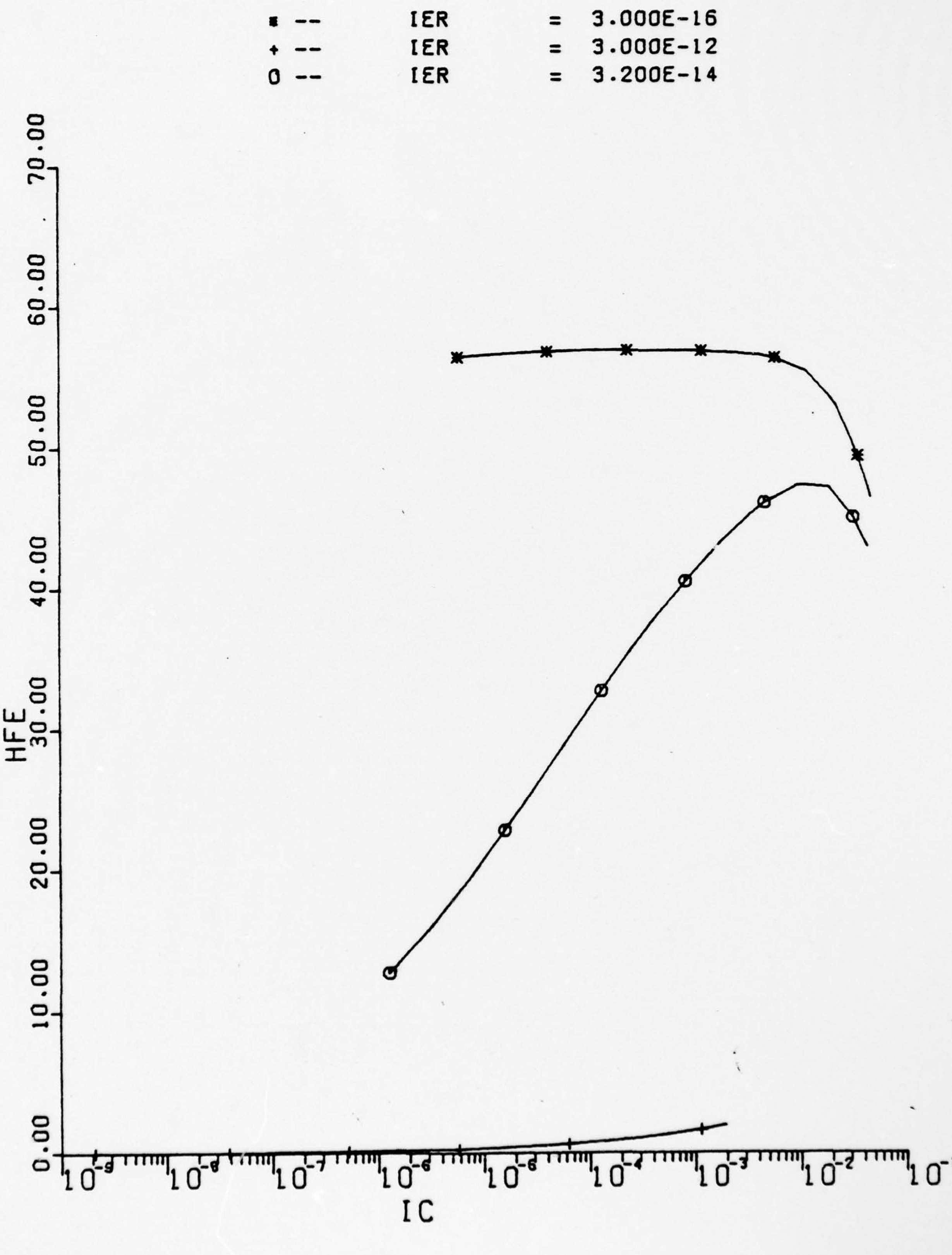


* -- PHIEO = 5.000E-01
+ -- PHIEO = 1.500E+00
0 -- PHIEO = 1.200E+00
HFE
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC

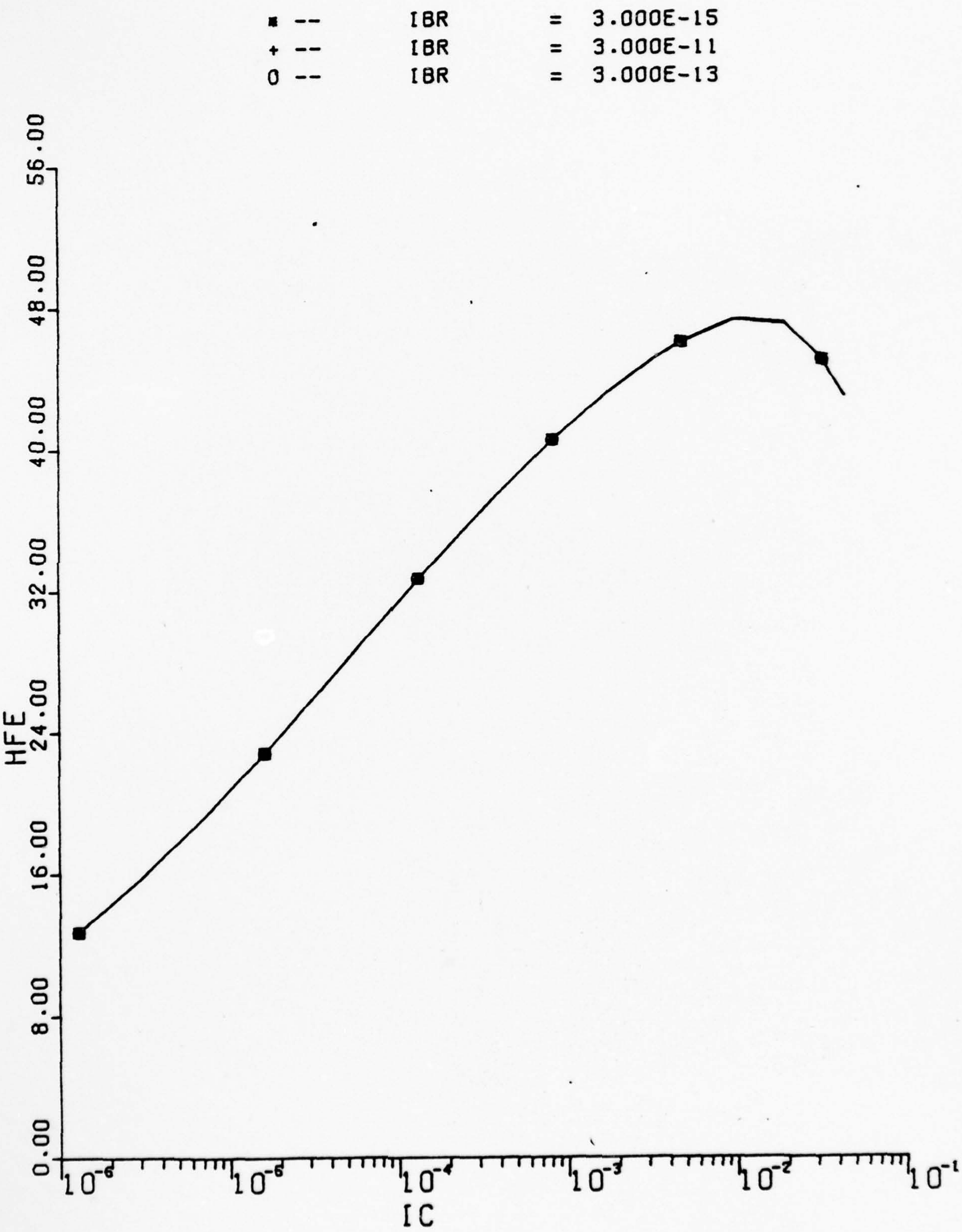


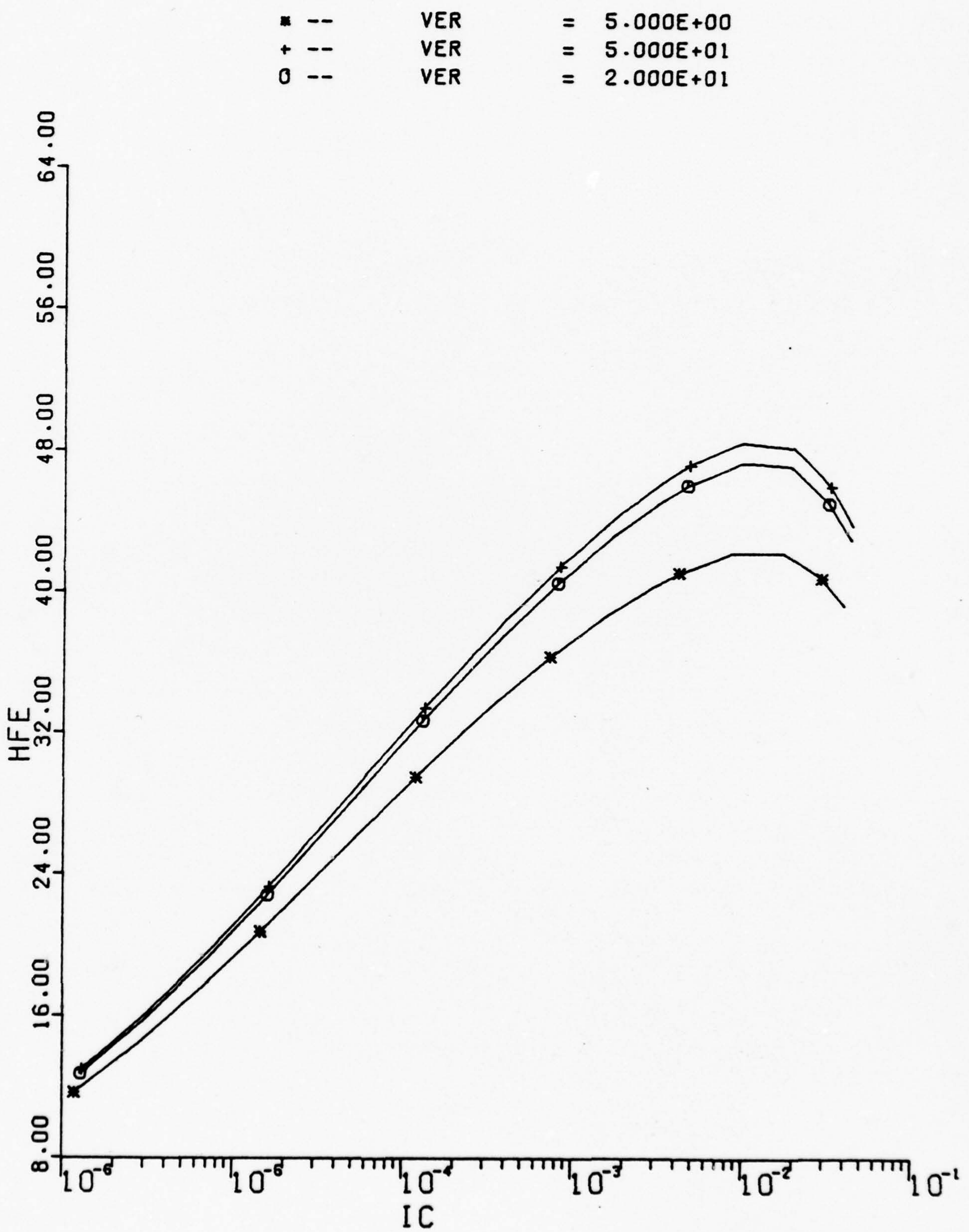
■ -- ISR = 3.000E-13
+ -- ISR = 3.000E-11
0 -- ISR = 3.000E-12
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
10-6
10-6
10-4
10-3
10-2
10-1
IC


* -- IS = 3.000E-18
+ -- IS = 3.000E-14
0 -- IS = 3.200E-16
HFE
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
IC
$10^{-8}$
$10^{-7}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

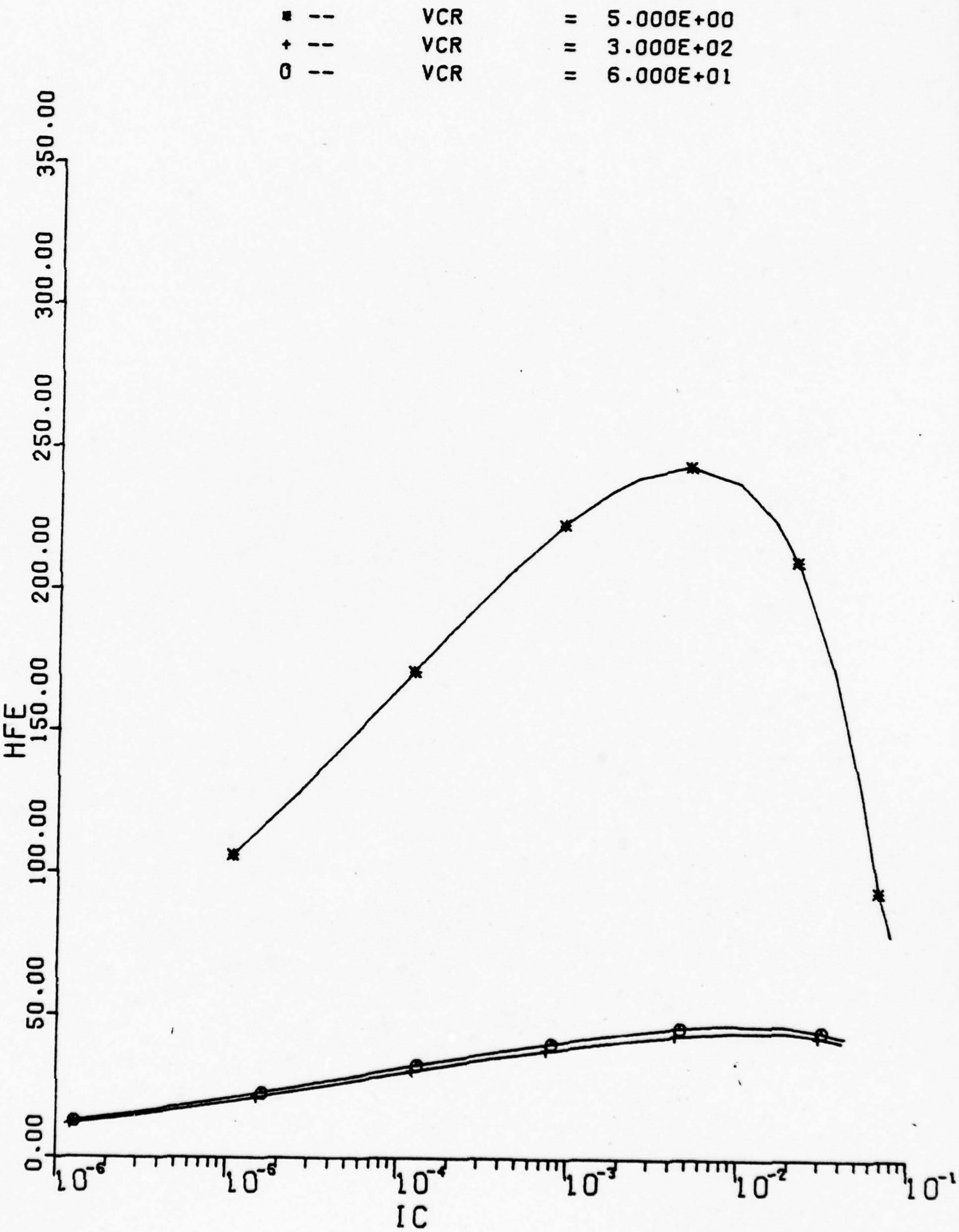


* -- IER = 3.000E-16
+ -- IER = 3.000E-12
O -- IER = 3.200E-14
HFE
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
IC
$10^{-9}$
$10^{-8}$
$10^{-7}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

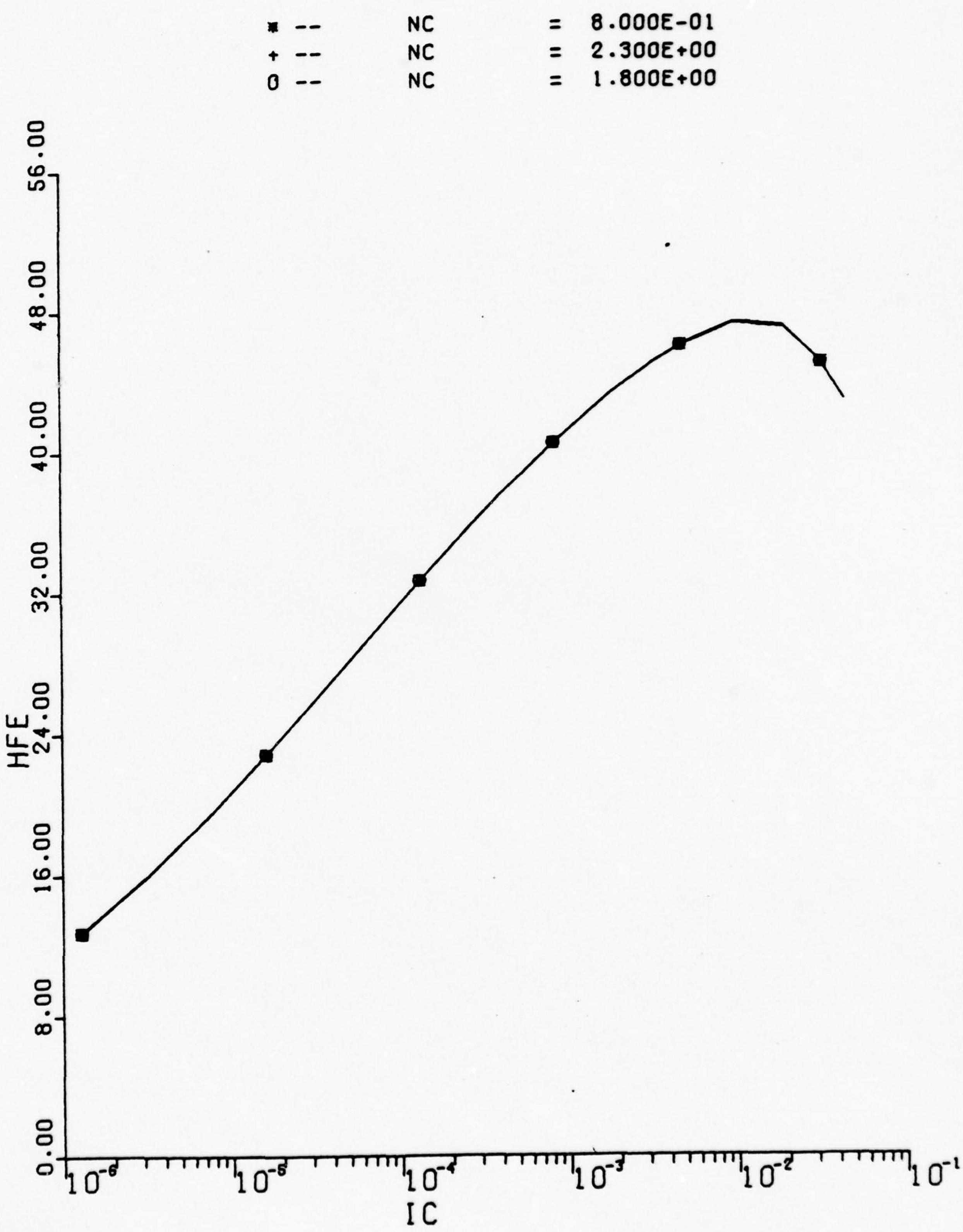

* -- IBR = 3.000E-15
+ -- IBR = 3.000E-11
0 -- IBR = 3.000E-13
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

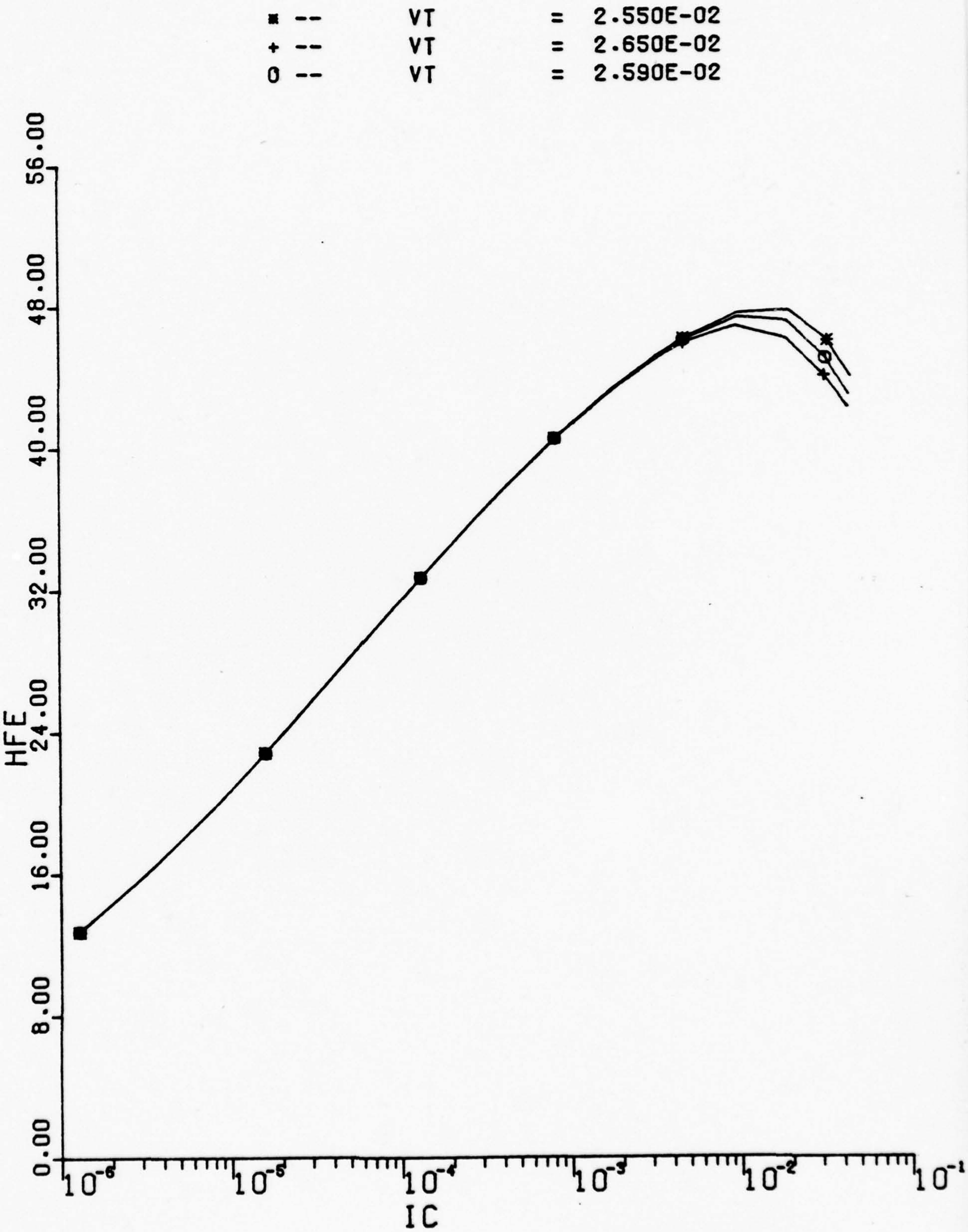


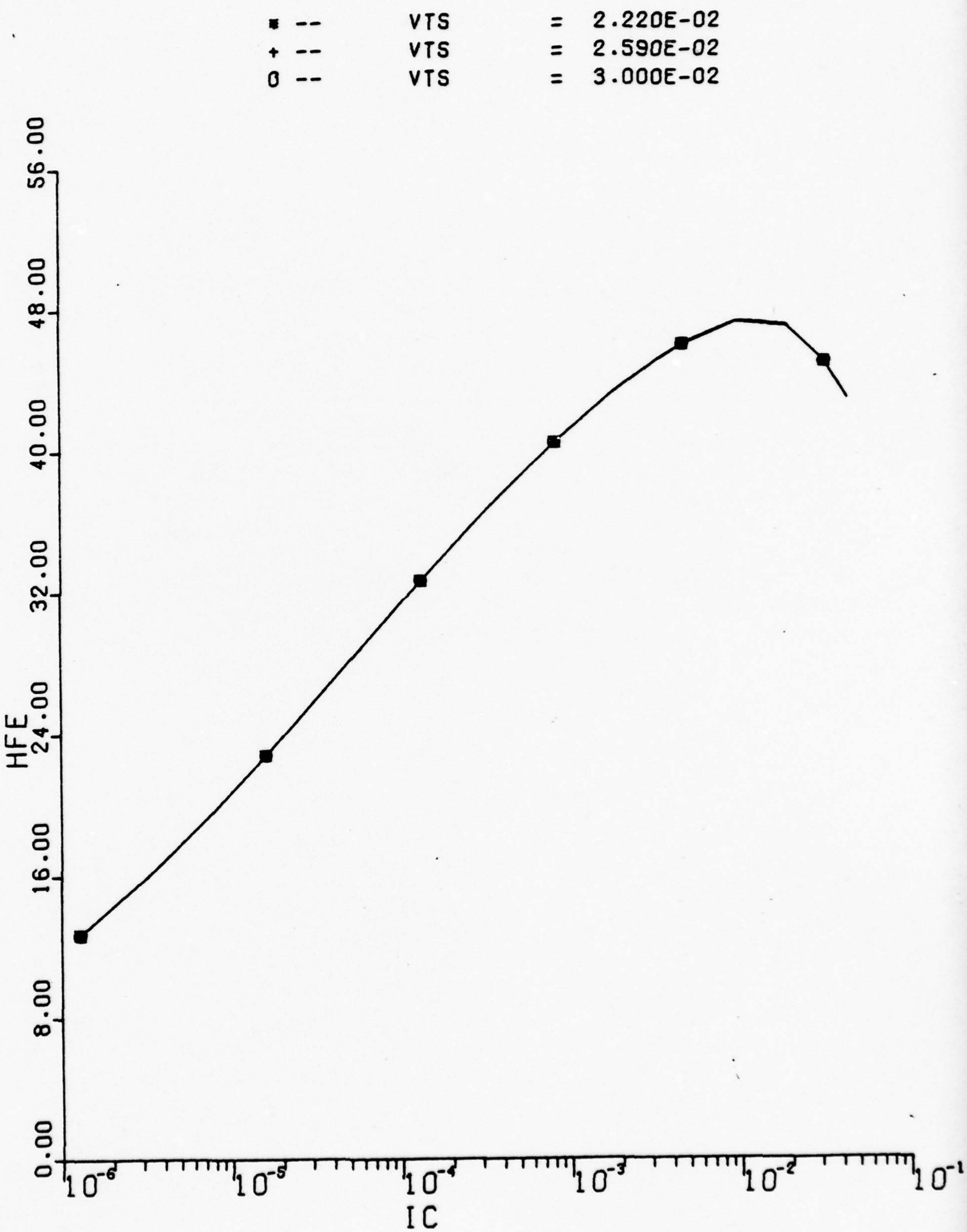
* -- VER = 5.000E+00
+ -- VER = 5.000E+01
0 -- VER = 2.000E+01
64.00
56.00
48.00
40.00
32.00
24.00
16.00
8.00
HFE
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC



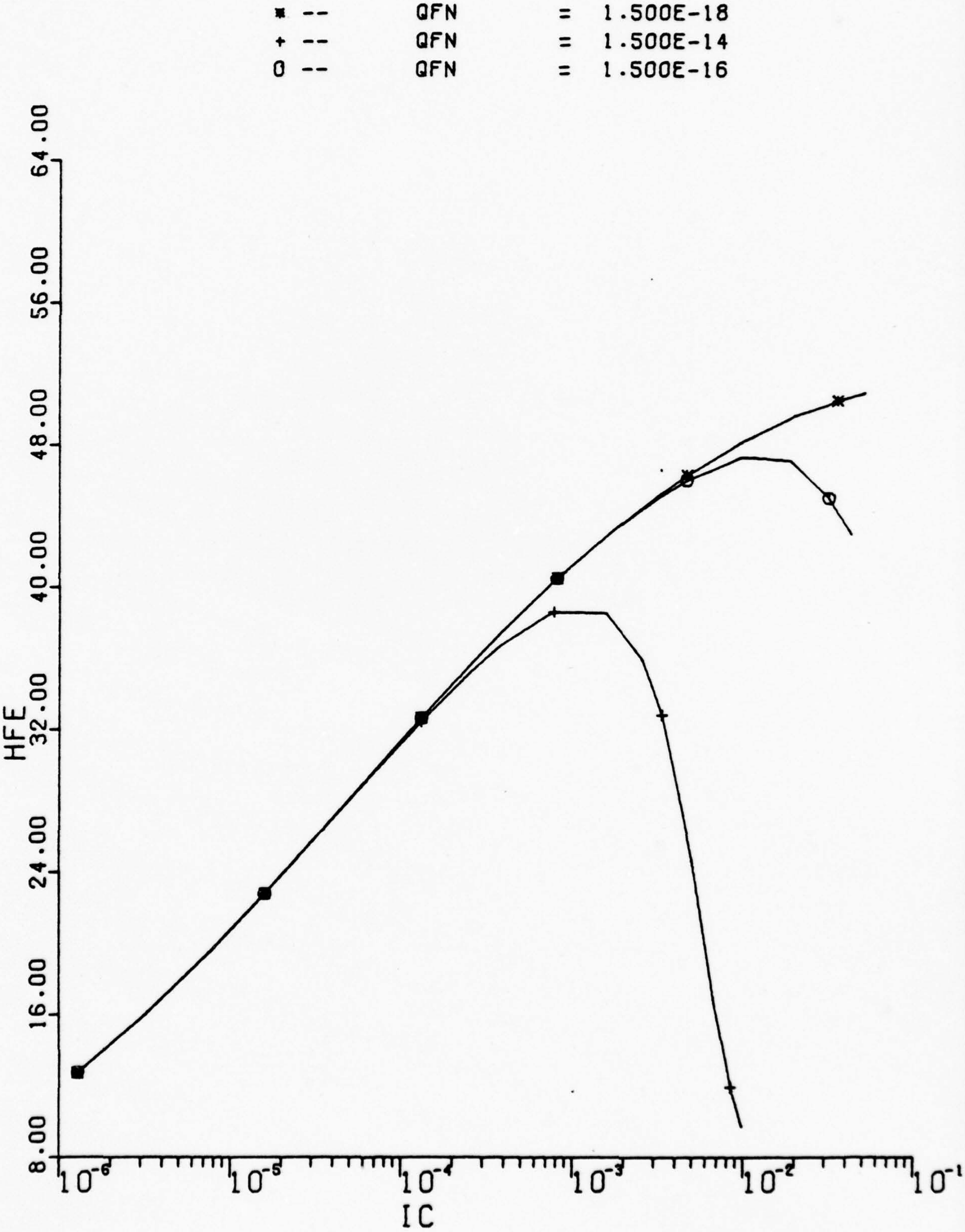
* -- VCR = 5.000E+00
+ -- VCR = 3.000E+02
0 -- VCR = 6.000E+01
HFE
0.00
50.00
100.00
150.00
200.00
250.00
300.00
350.00
IC


* -- NC = 8.000E-01
+ -- NC = 2.300E+00
0 -- NC = 1.800E+00
HFE
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

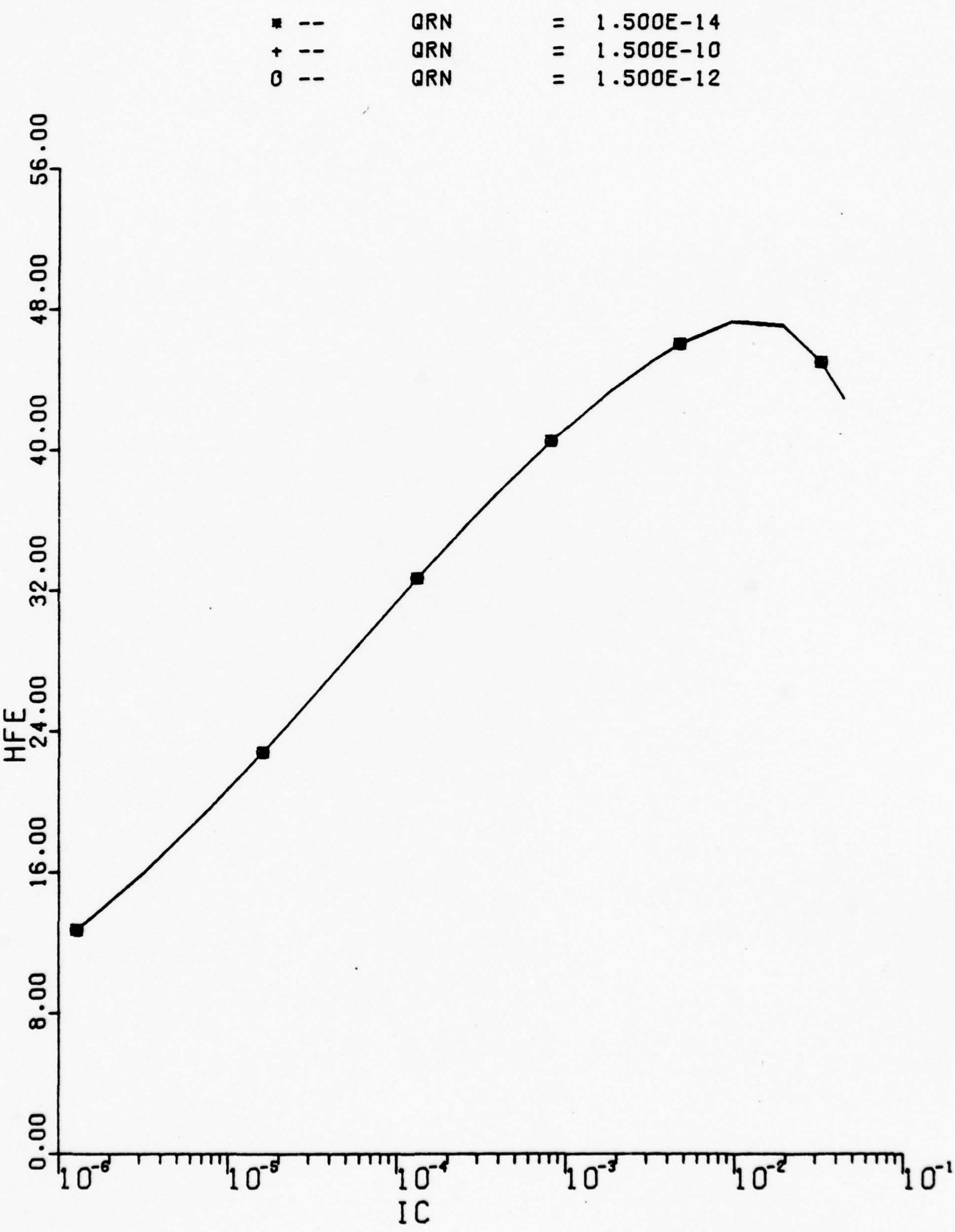

* -- VT = 2.550E-02
+ -- VT = 2.650E-02
O -- VT = 2.590E-02
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
HFE
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC



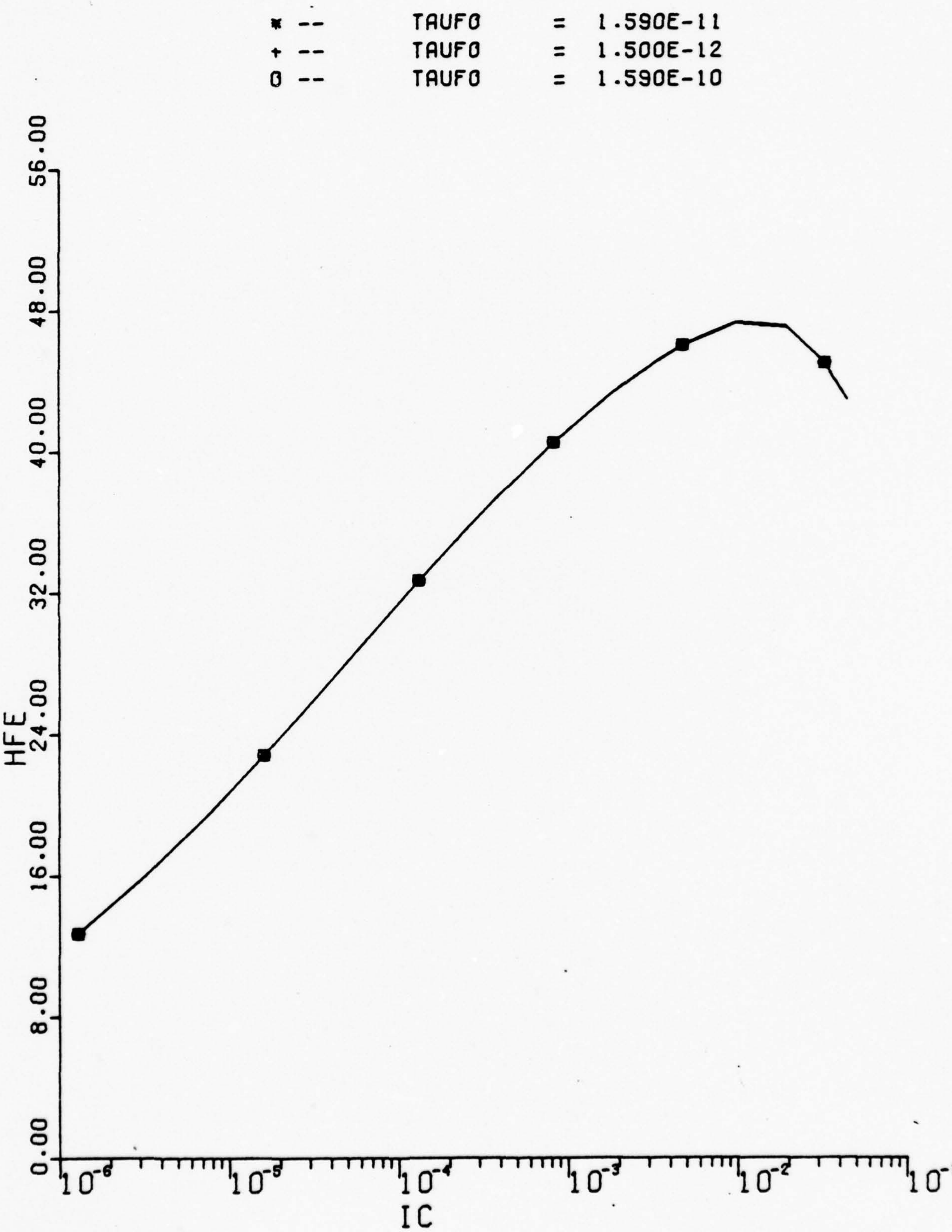
* -- VTS = 2.220E-02
+ -- VTS = 2.590E-02
0 -- VTS = 3.000E-02
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$



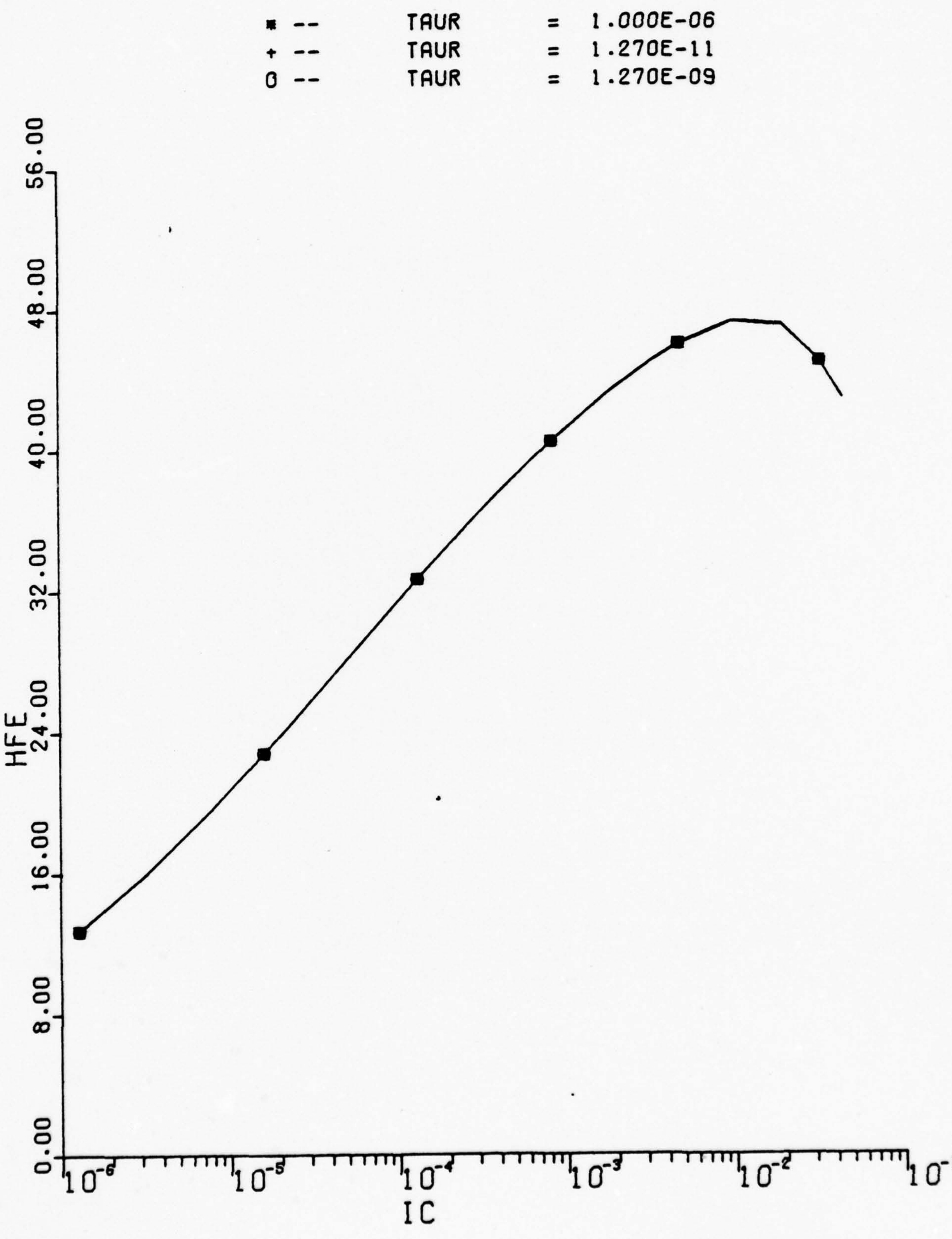
* -- QFN = 1.500E-18
+ -- QFN = 1.500E-14
O -- QFN = 1.500E-16
HFE
64.00
56.00
48.00
40.00
32.00
24.00
16.00
8.00
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC



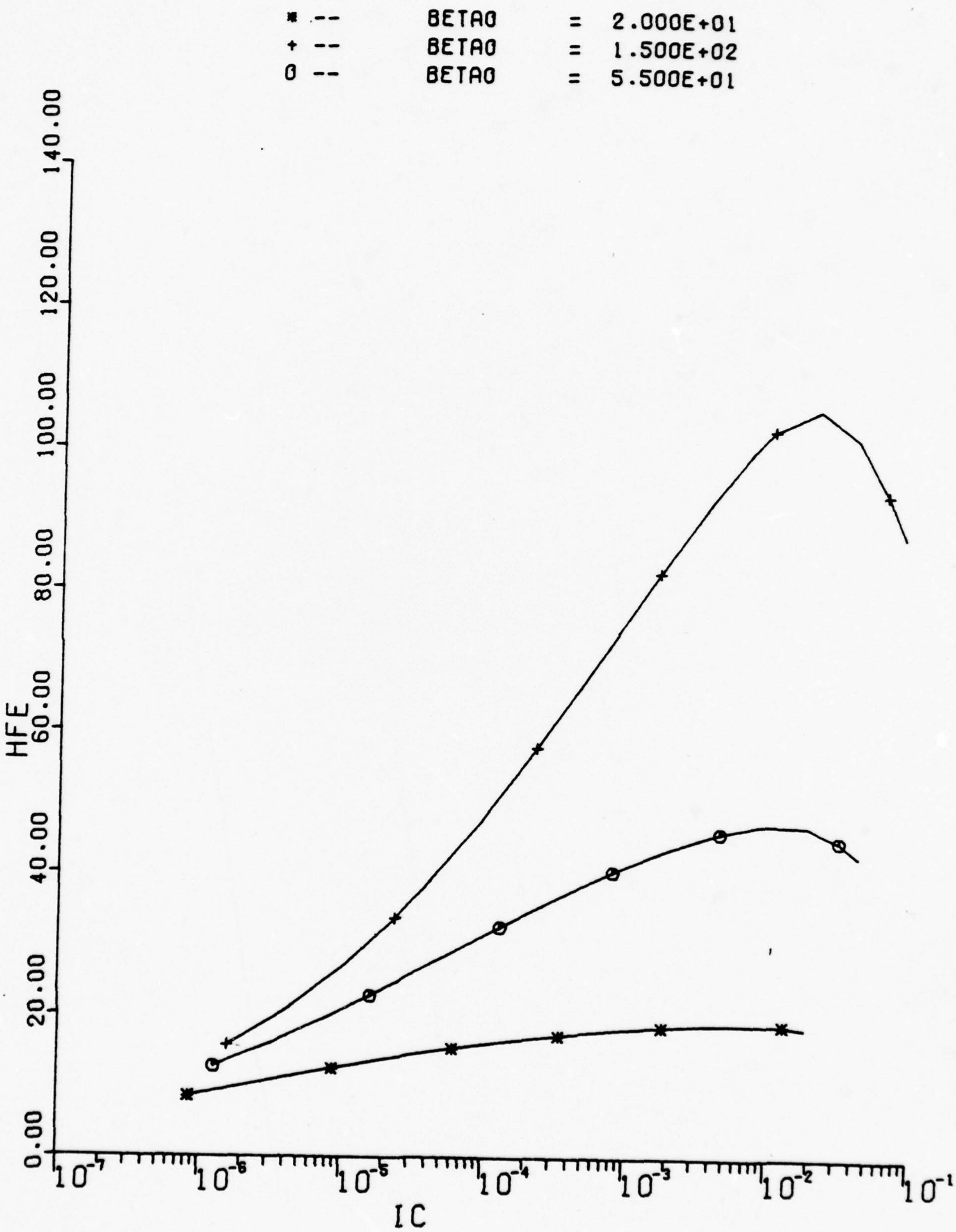
* -- QRN = 1.500E-14
+ -- QRN = 1.500E-10
0 -- QRN = 1.500E-12
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
IC
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1



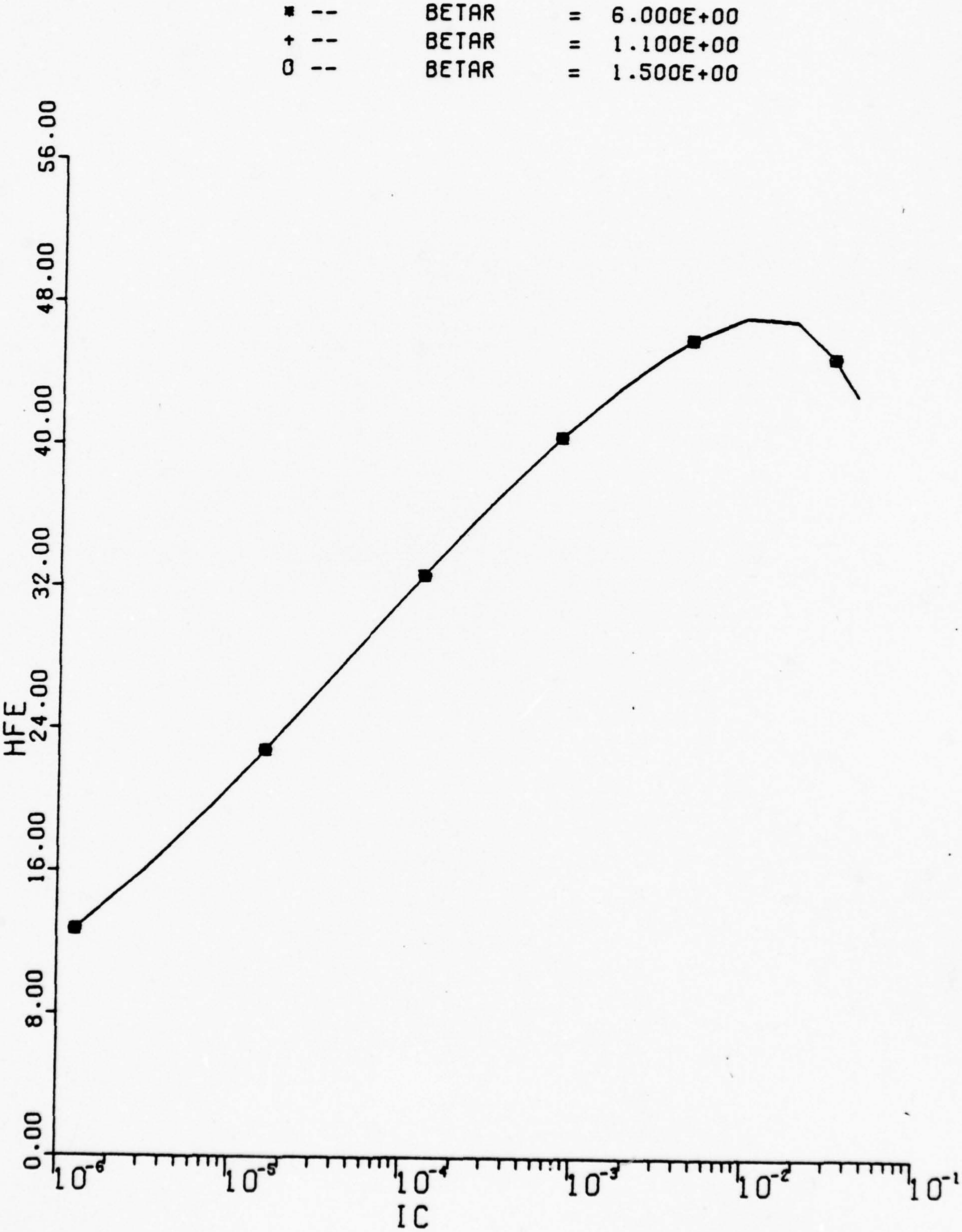
* -- TAUFO = 1.590E-11
+ -- TAUFO = 1.500E-12
O -- TAUFO = 1.590E-10
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
HFE
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC



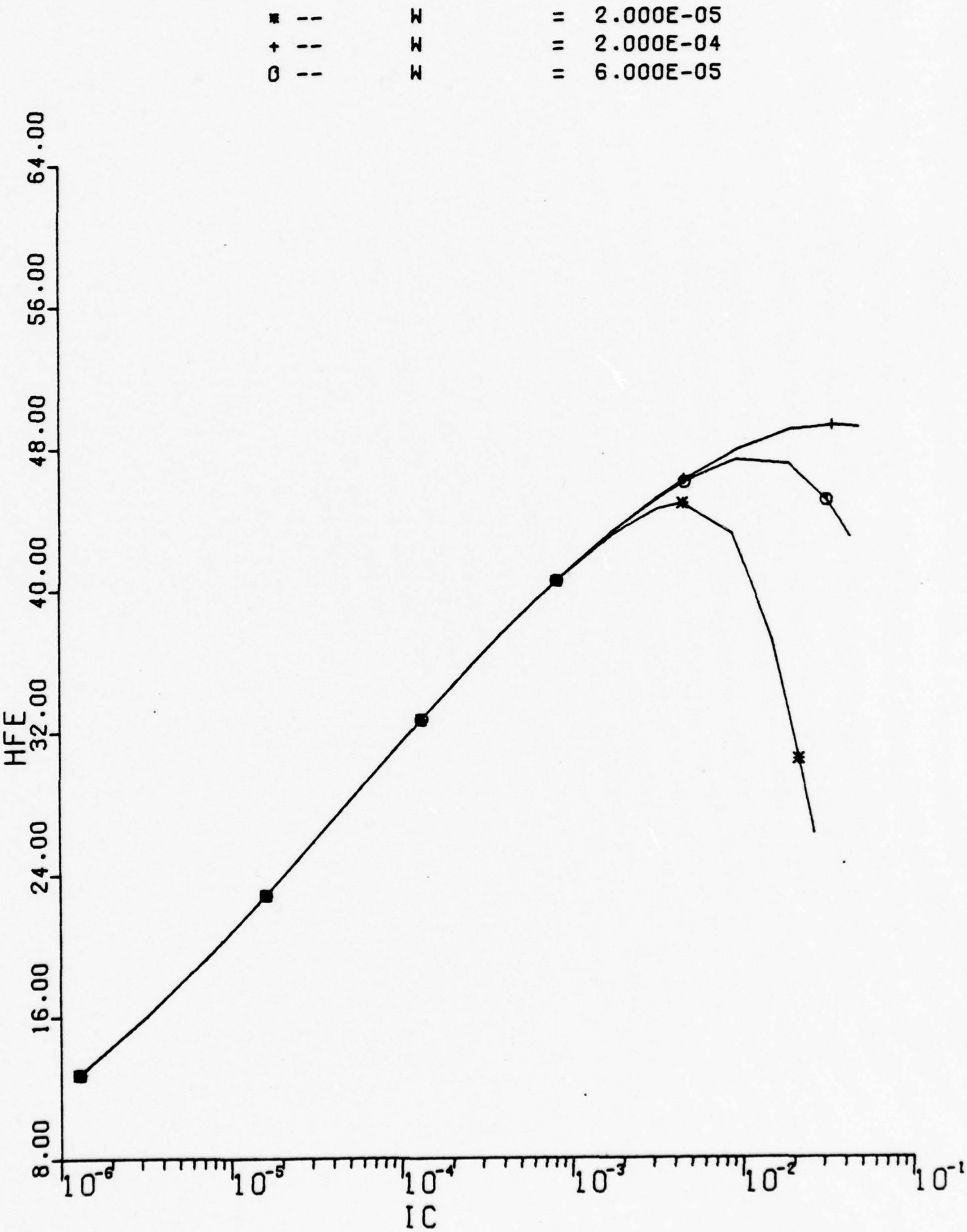
* -- TAUR = 1.000E-06
+ -- TAUR = 1.270E-11
O -- TAUR = 1.270E-09
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC

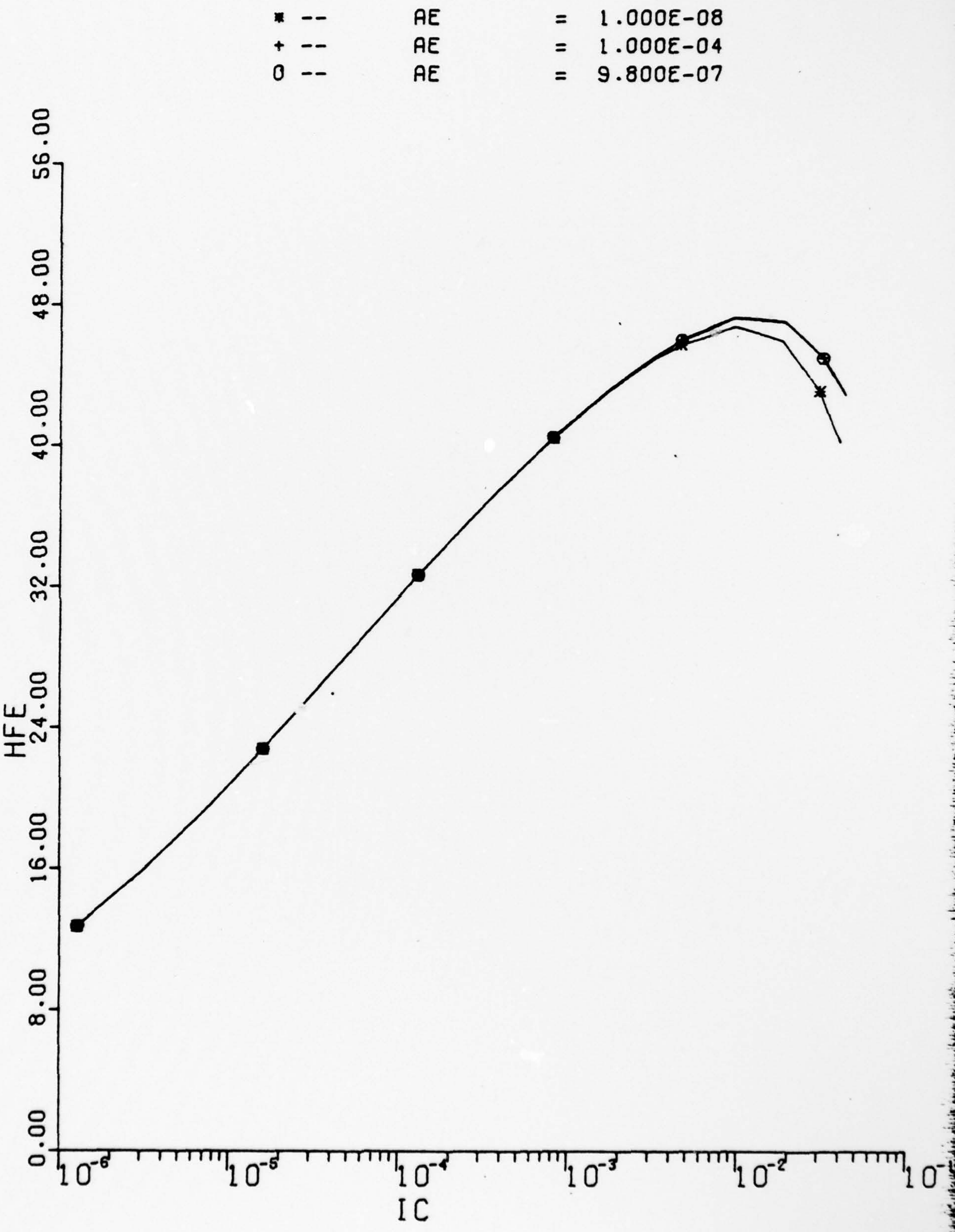


* -- BETAO = 2.000E+01
+ -- BETAO = 1.500E+02
O -- BETAO = 5.500E+01
HFE
0.00
20.00
40.00
60.00
80.00
100.00
120.00
140.00
IC
$10^{-7}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

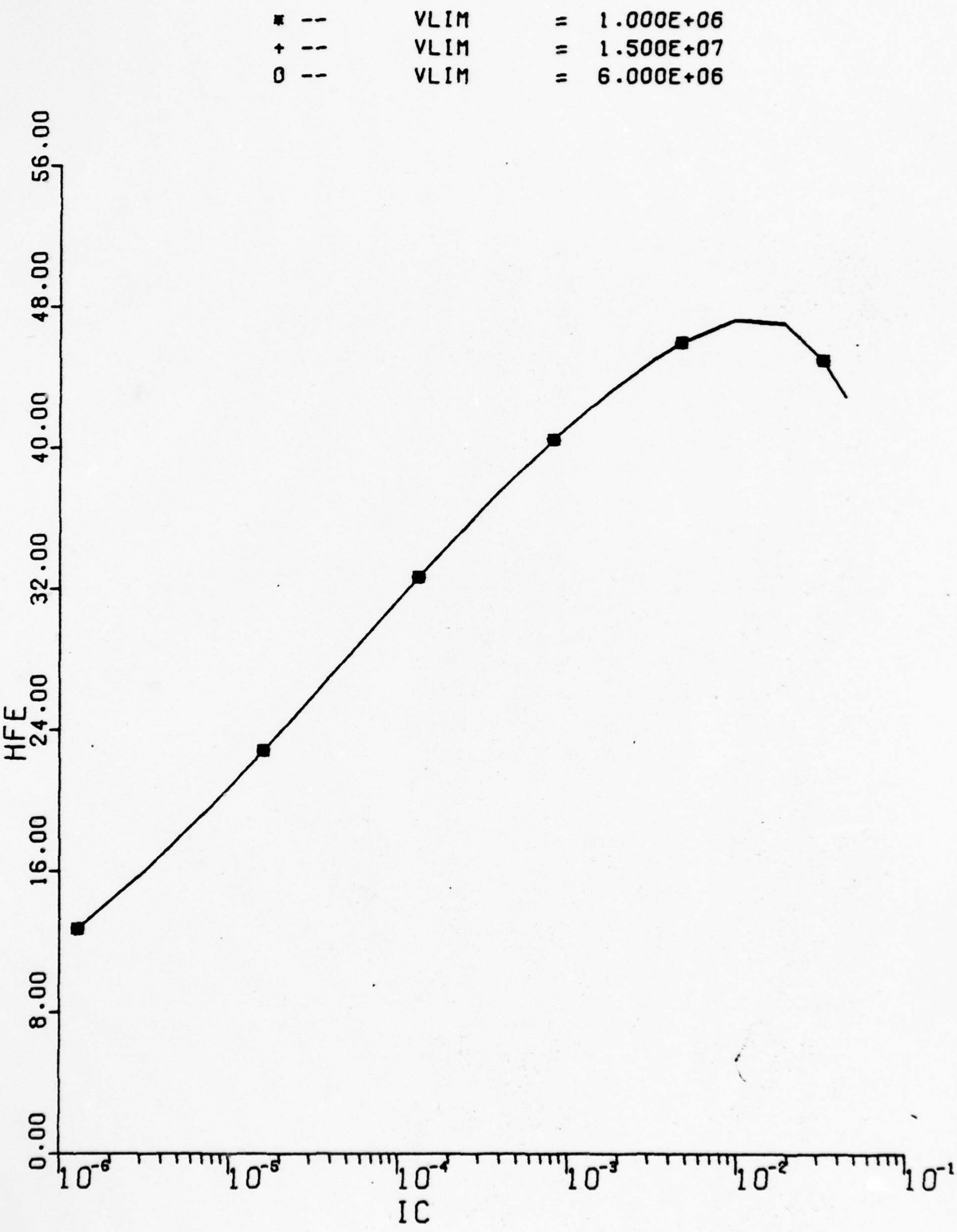


* -- BETAR = 6.000E+00
+ -- BETAR = 1.100E+00
0 -- BETAR = 1.500E+00
HFE
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

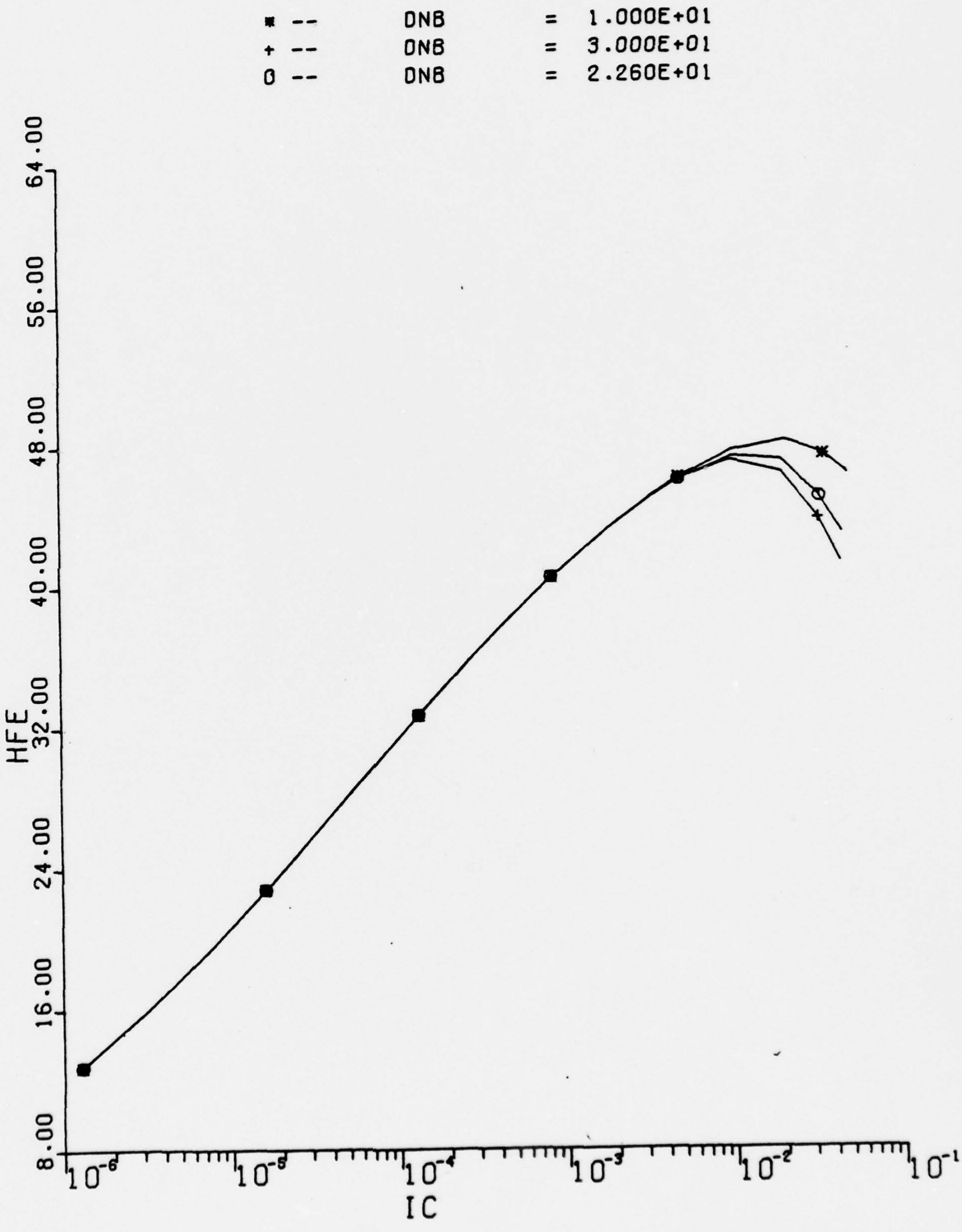

* -- W = 2.000E-05
+ -- W = 2.000E-04
0 -- W = 6.000E-05
HFE
64.00
56.00
48.00
40.00
32.00
24.00
16.00
8.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

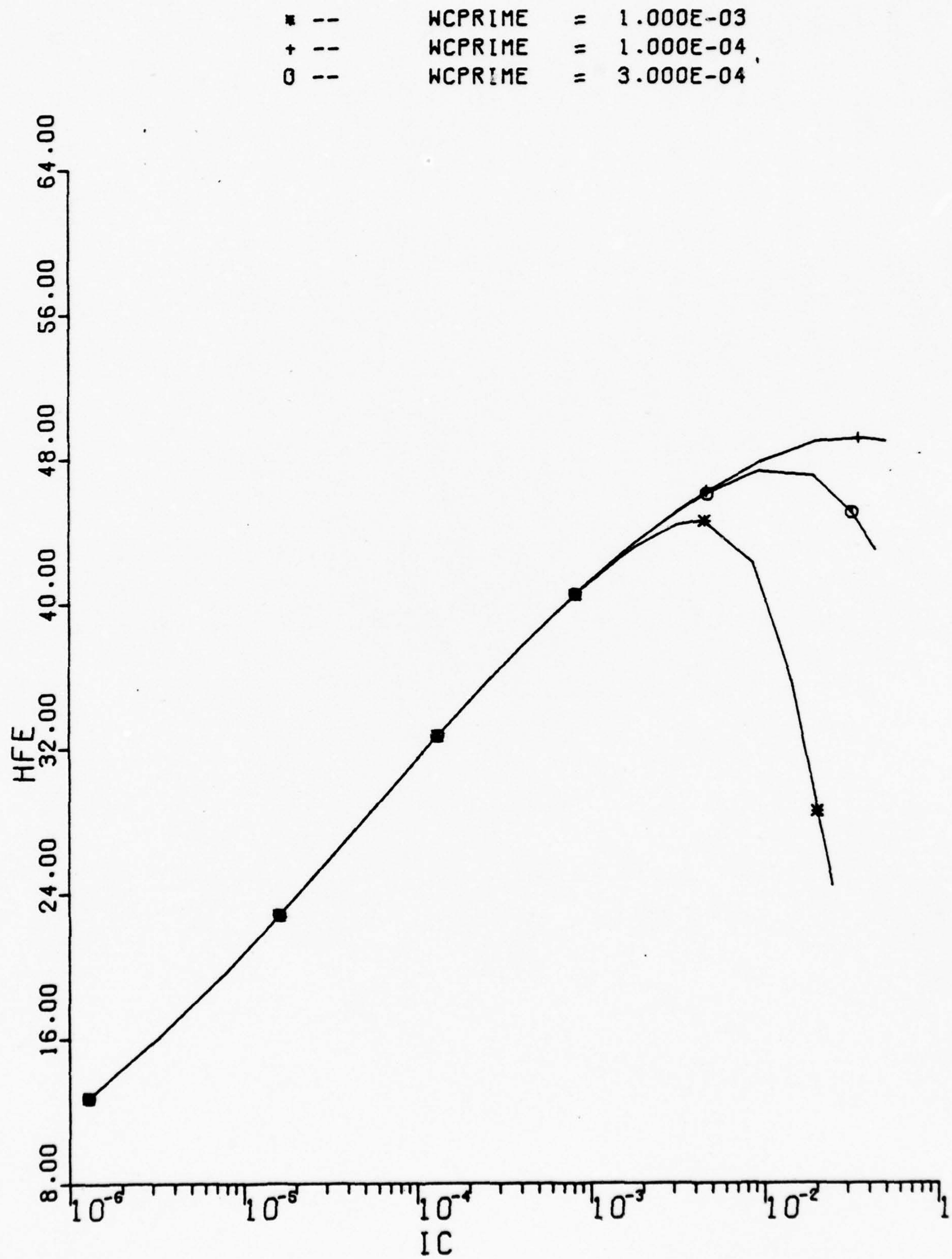


* -- AE = 1.000E-08
+ -- AE = 1.000E-04
0 -- AE = 9.800E-07
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
HFE
IC

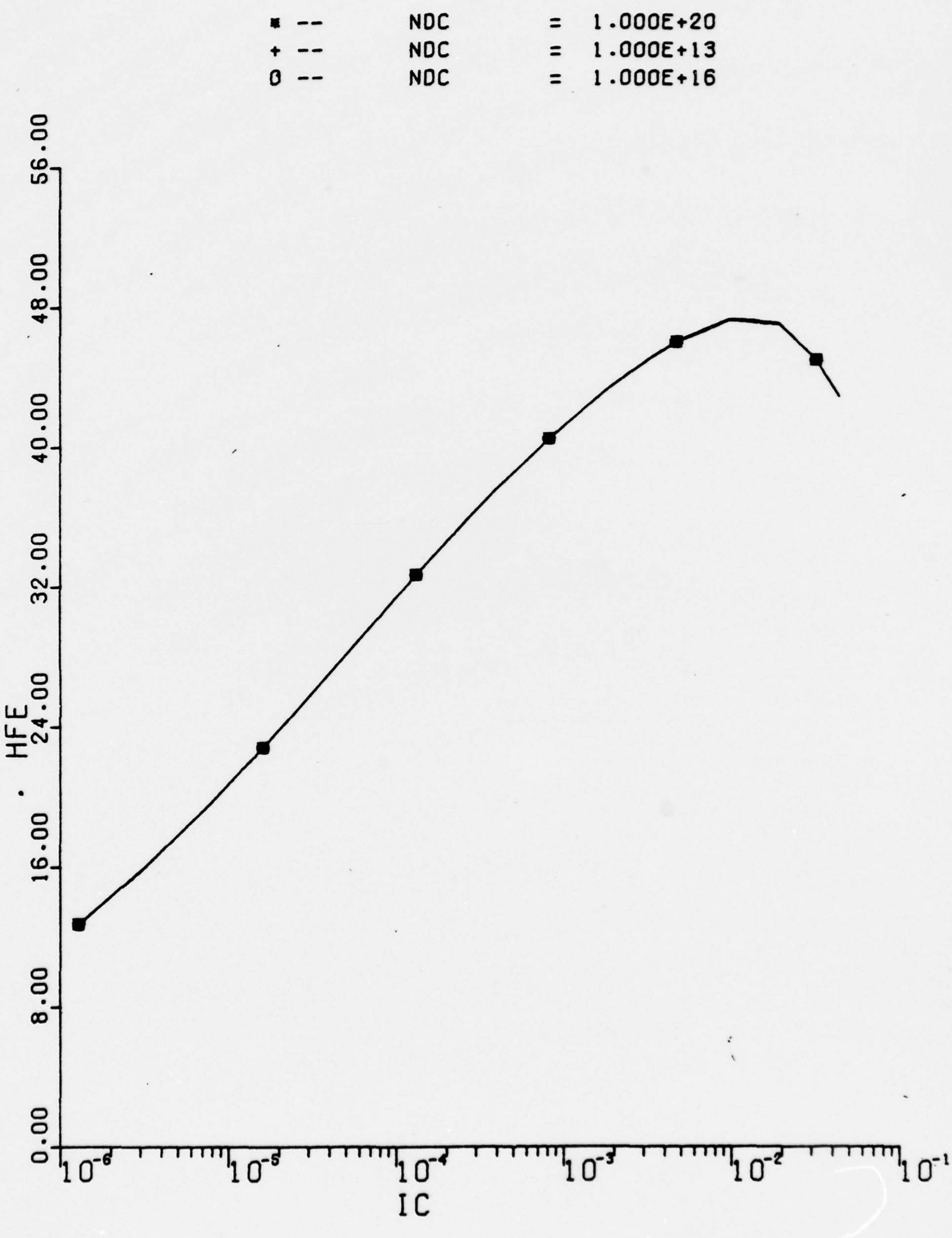


* -- VLIM = 1.000E+06
+ -- VLIM = 1.500E+07
0 -- VLIM = 6.000E+06
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

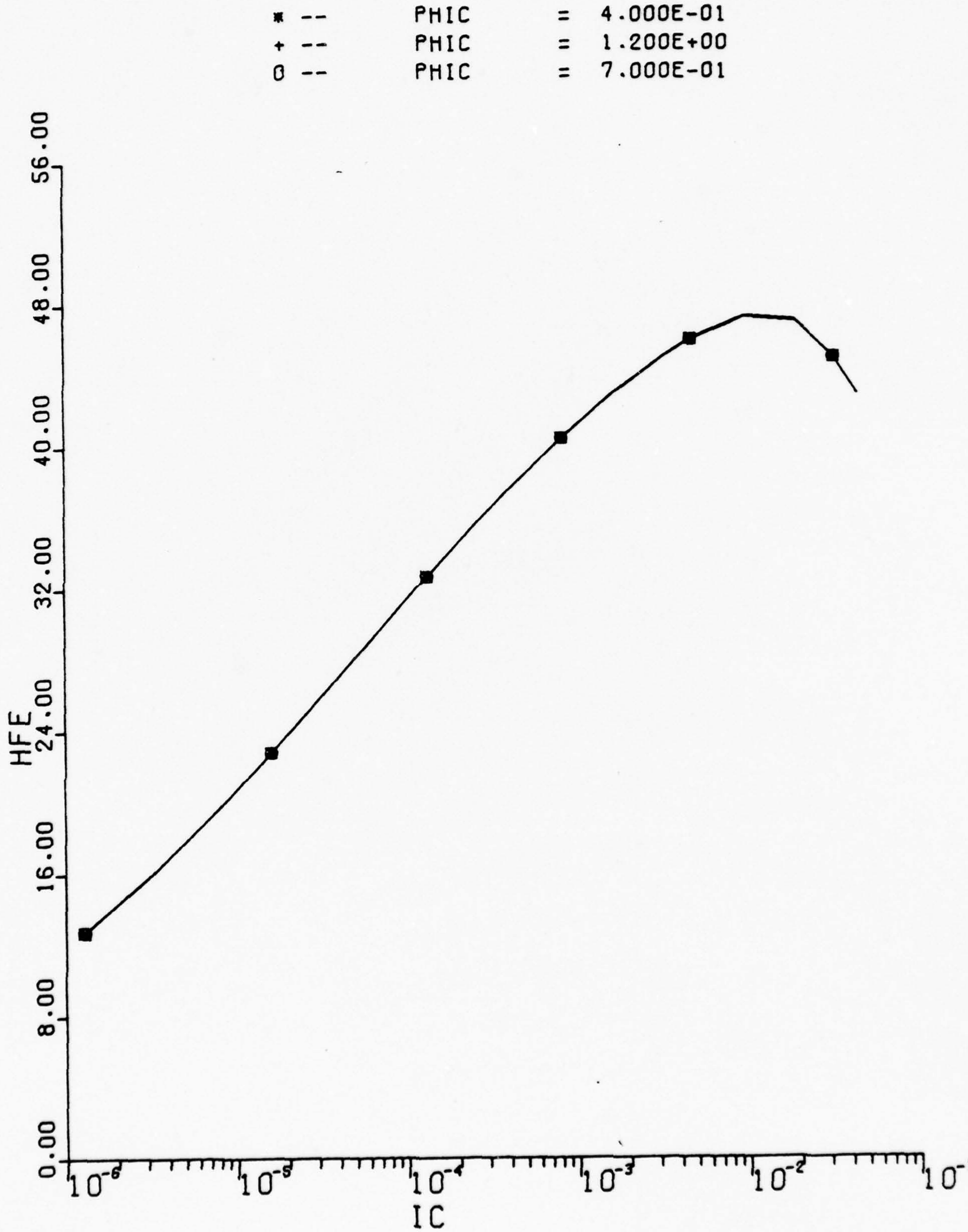

* -- DNB = 1.000E+01
+ -- DNB = 3.000E+01
0 -- DNB = 2.260E+01
HFE
64.00
56.00
48.00
40.00
32.00
24.00
16.00
8.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

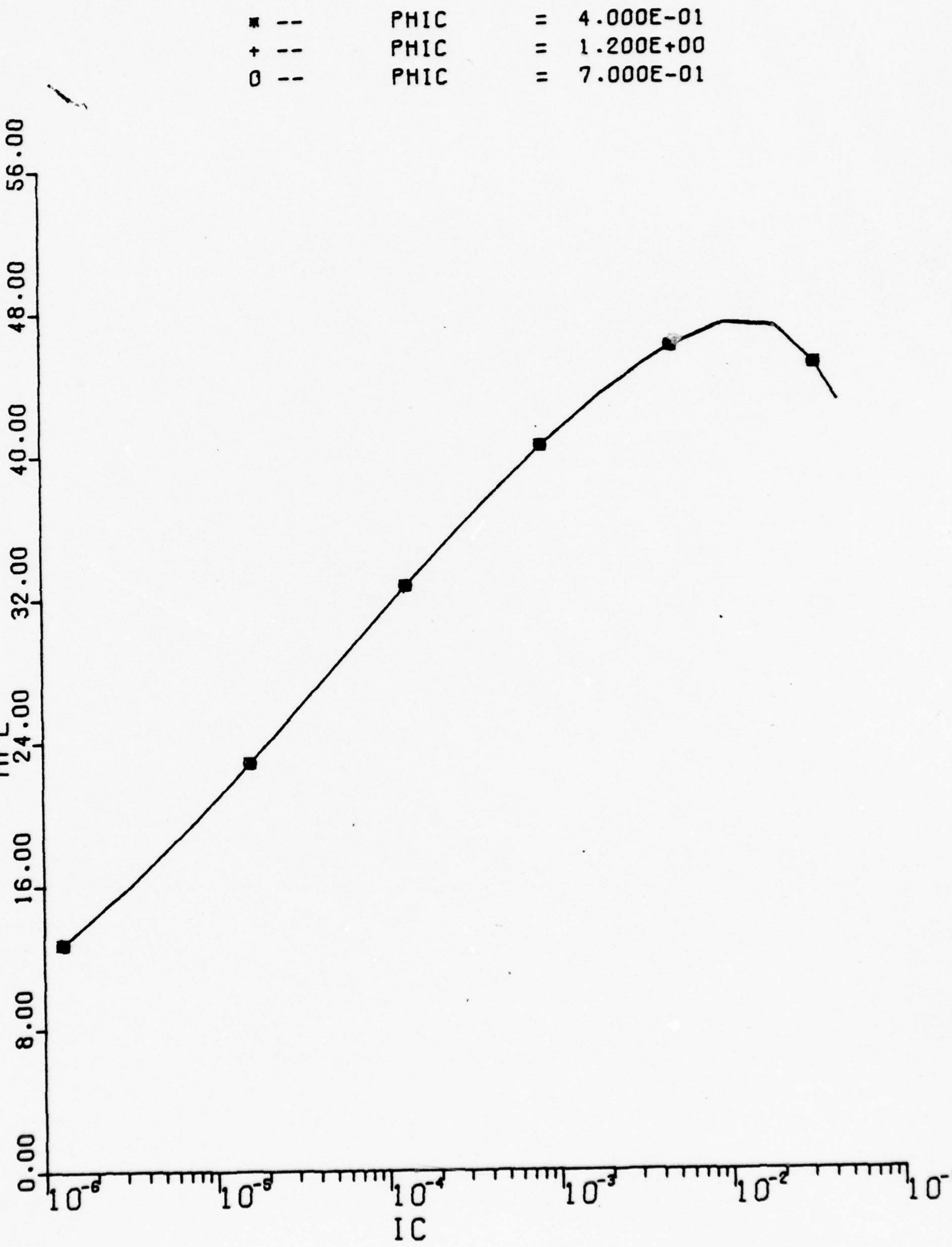


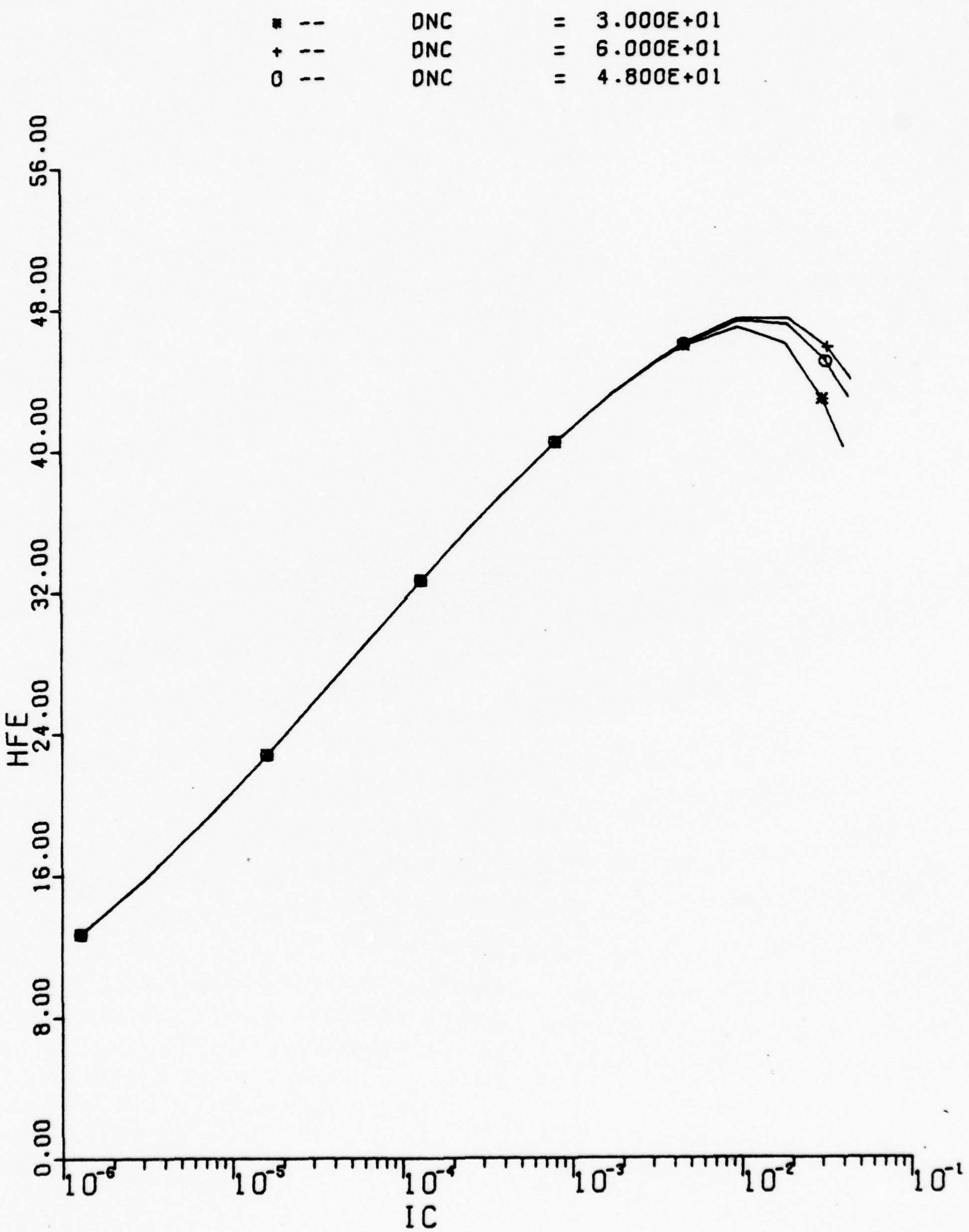
* -- WCPRIME = 1.000E-03
+ -- WCPRIME = 1.000E-04
O -- WCPRIME = 3.000E-04
64.00
56.00
48.00
40.00
32.00
24.00
16.00
8.00
HFE
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC

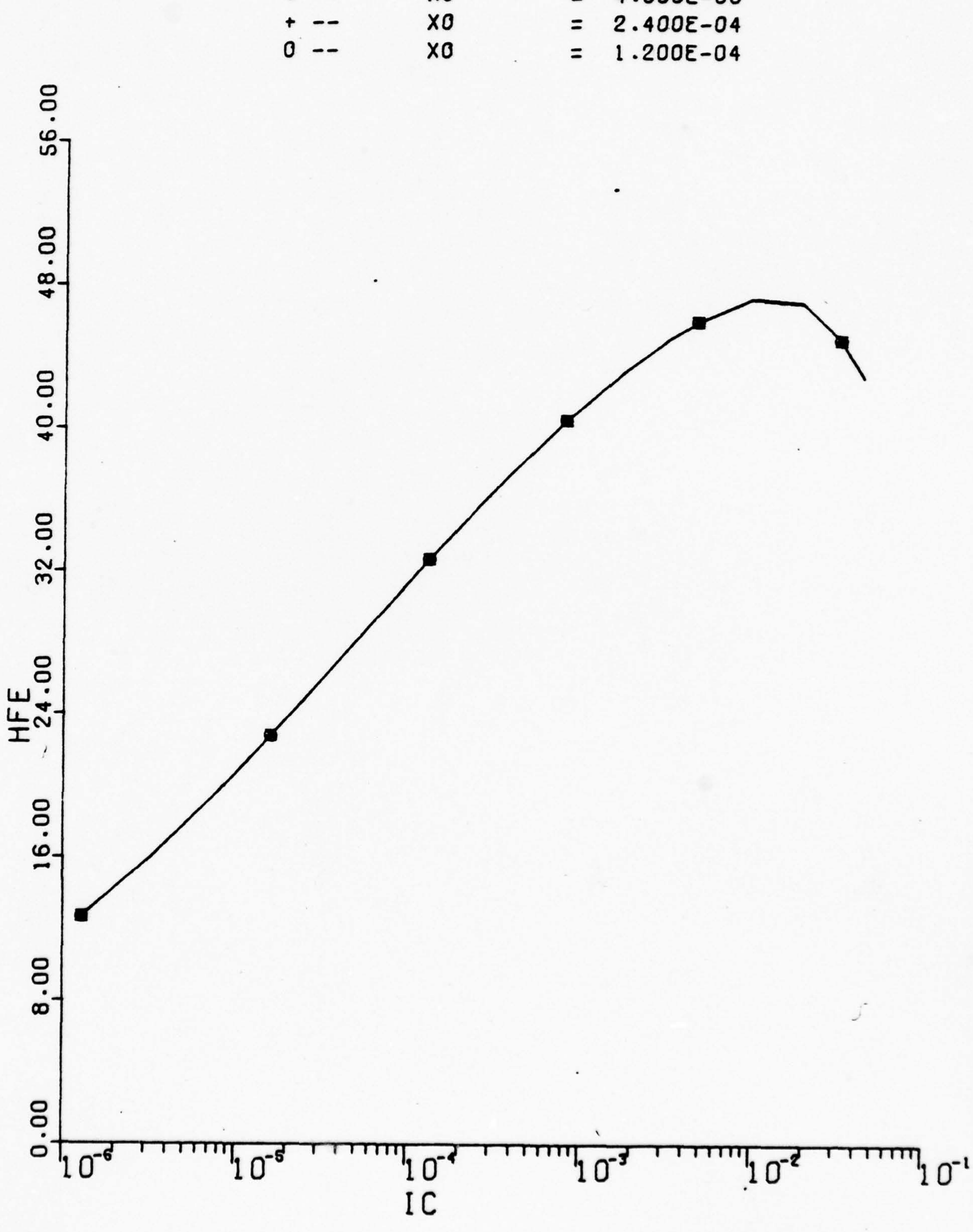


* -- NDC = 1.000E+20
+ -- NDC = 1.000E+13
0 -- NDC = 1.000E+16
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC

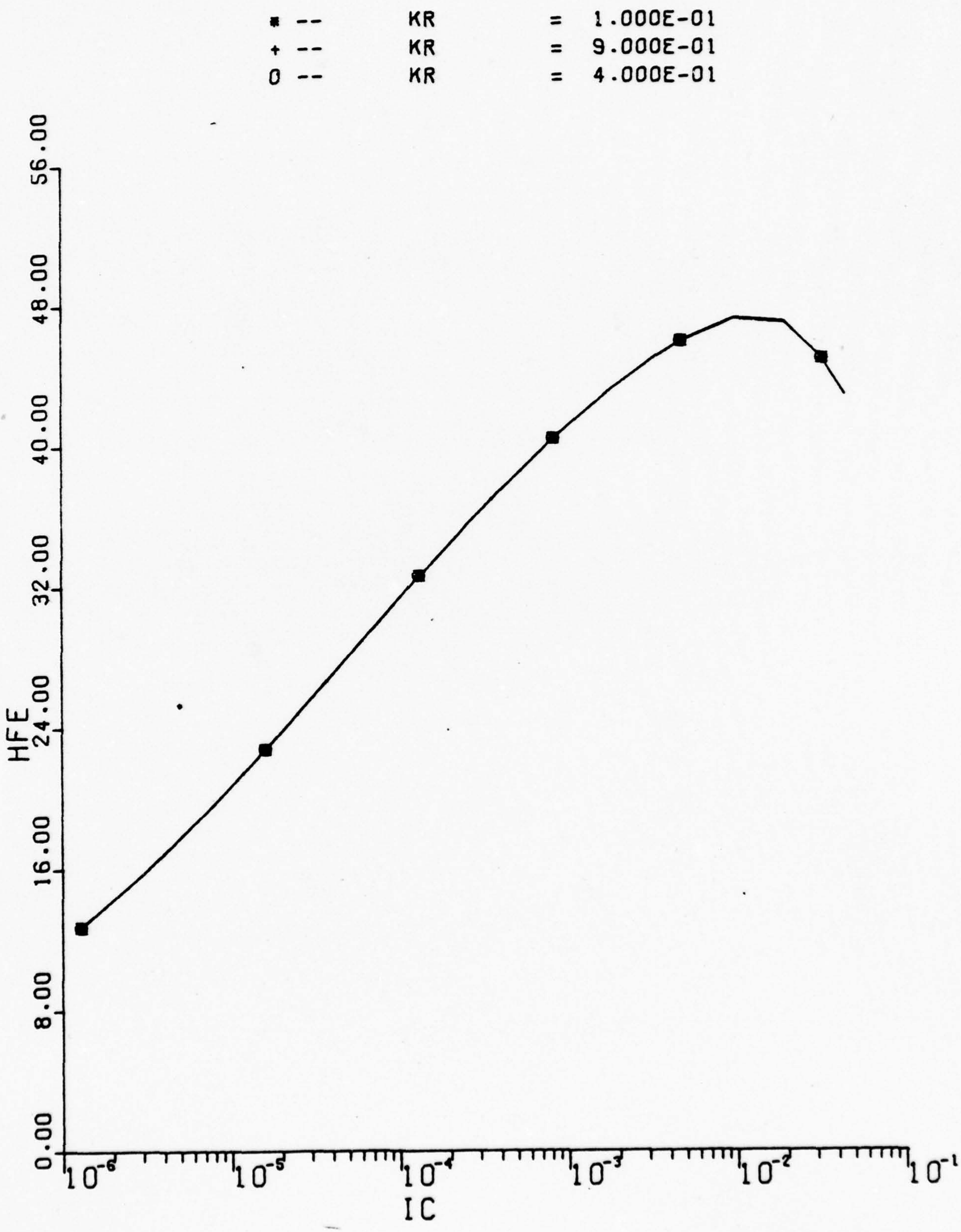

* -- PHIC = 4.000E-01
+ -- PHIC = 1.200E+00
0 -- PHIC = 7.000E-01
HFE
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC


* -- PHIC = 4.000E-01
+ -- PHIC = 1.200E+00
0 -- PHIC = 7.000E-01
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

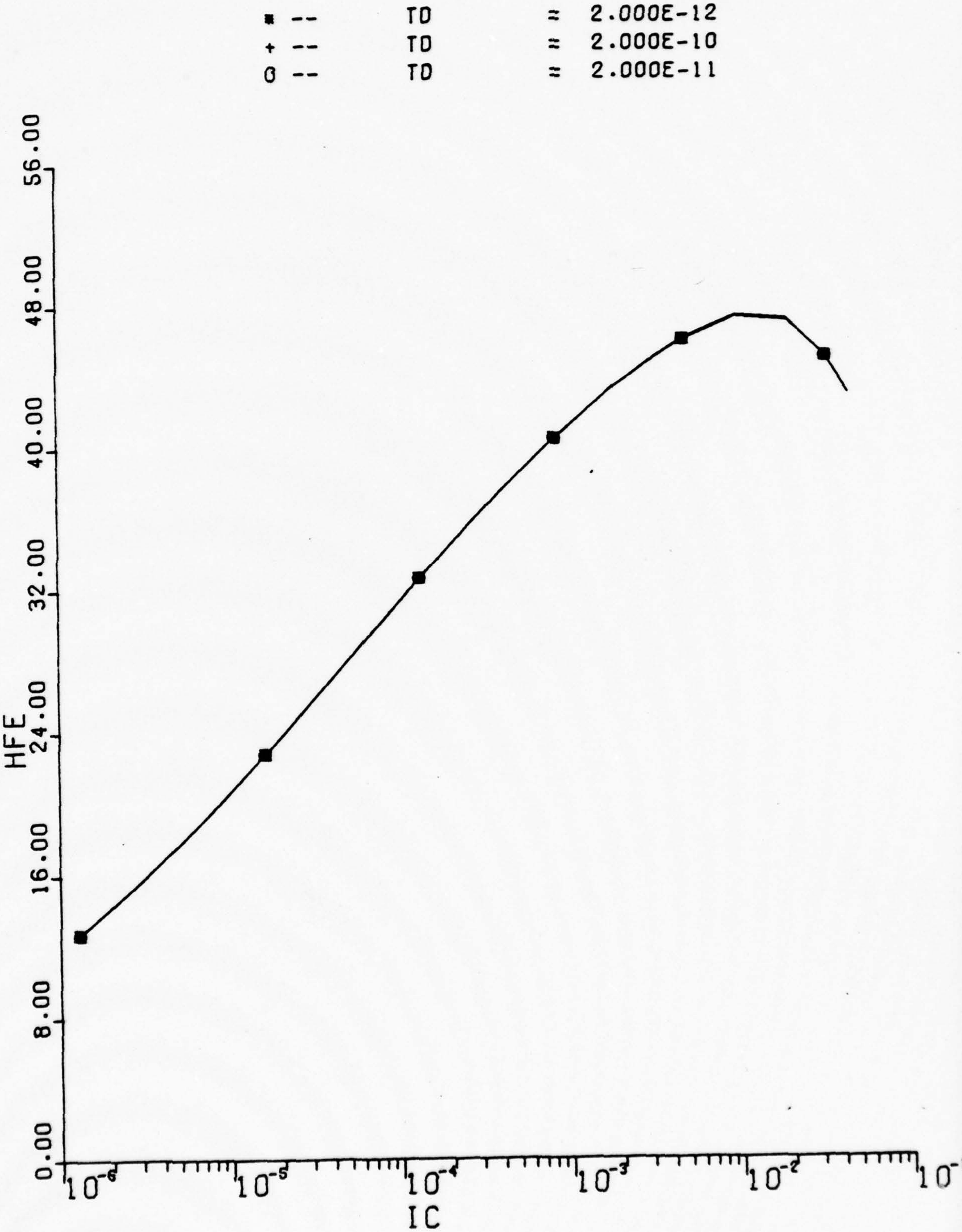

* -- DNC = 3.000E+01
+ -- DNC = 6.000E+01
O -- DNC = 4.800E+01
HFE
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC



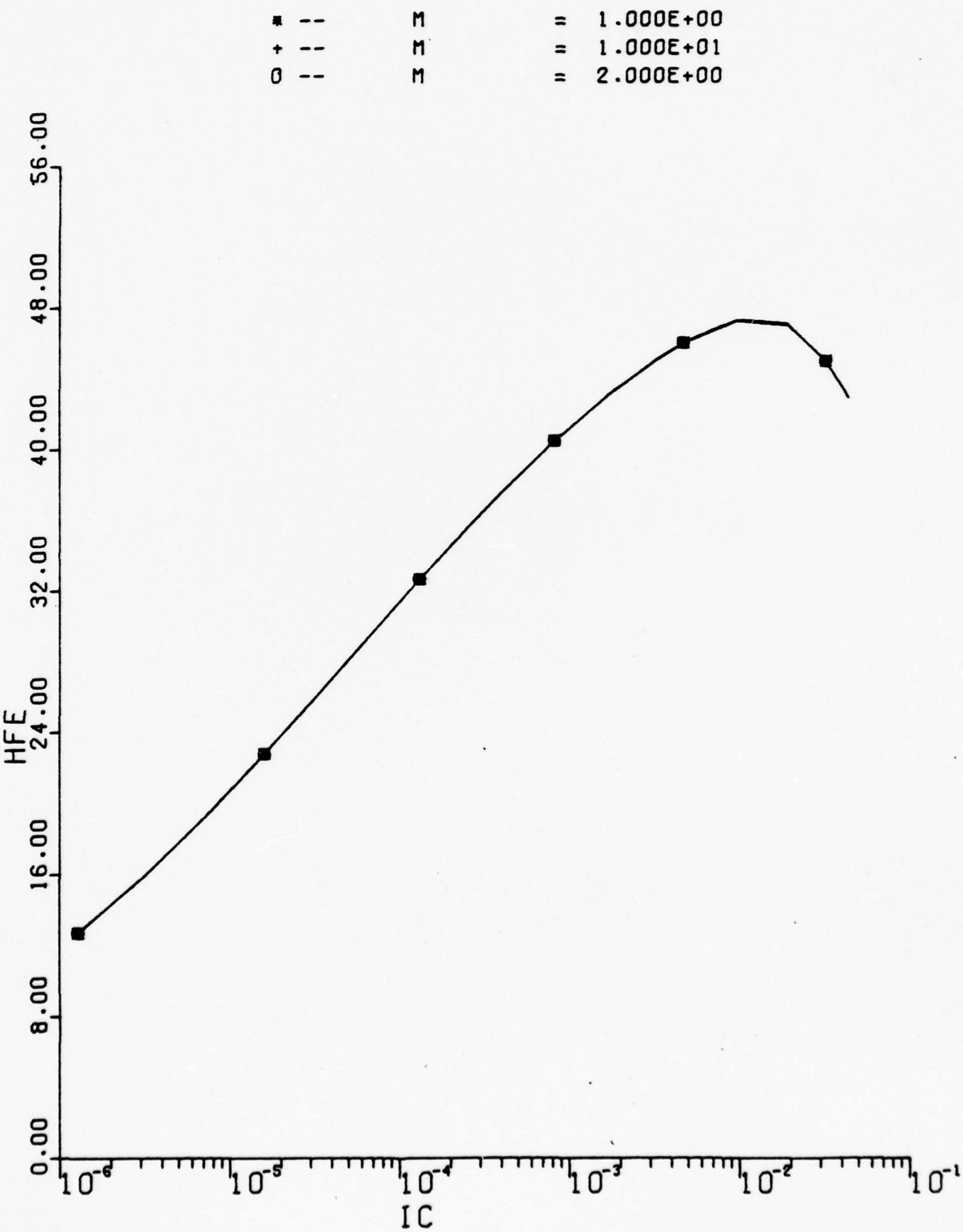
* -- X0 = 4.000E-05
+ -- X0 = 2.400E-04
0 -- X0 = 1.200E-04
HFE
56.00
48.00
40.00
32.00
24.00
16.00
8.00
0.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$



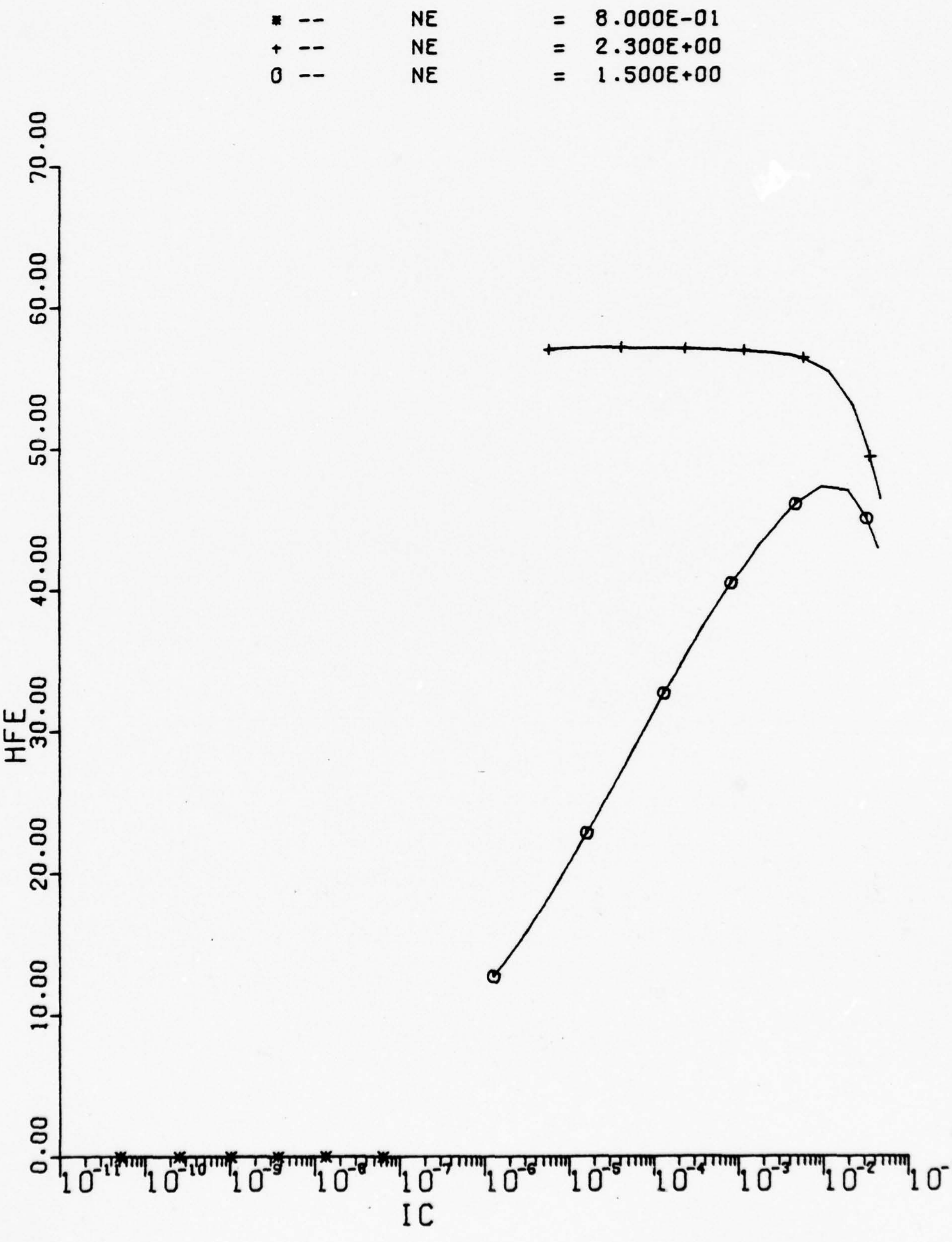
* -- KR = 1.000E-01
+ -- KR = 9.000E-01
0 -- KR = 4.000E-01
HFE
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$



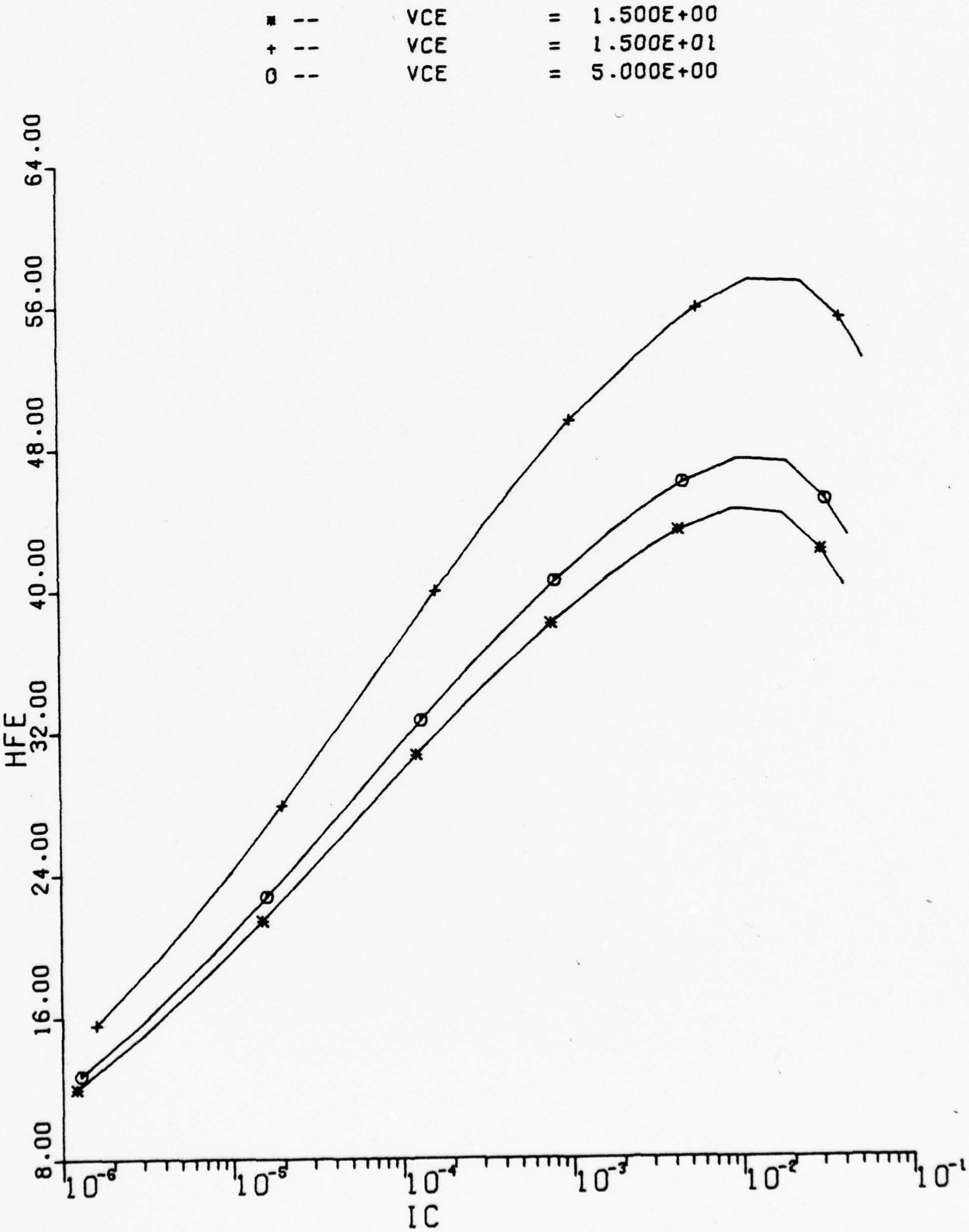
* -- TD = 2.000E-12
+ -- TD = 2.000E-10
0 -- TD = 2.000E-11
HFE
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$



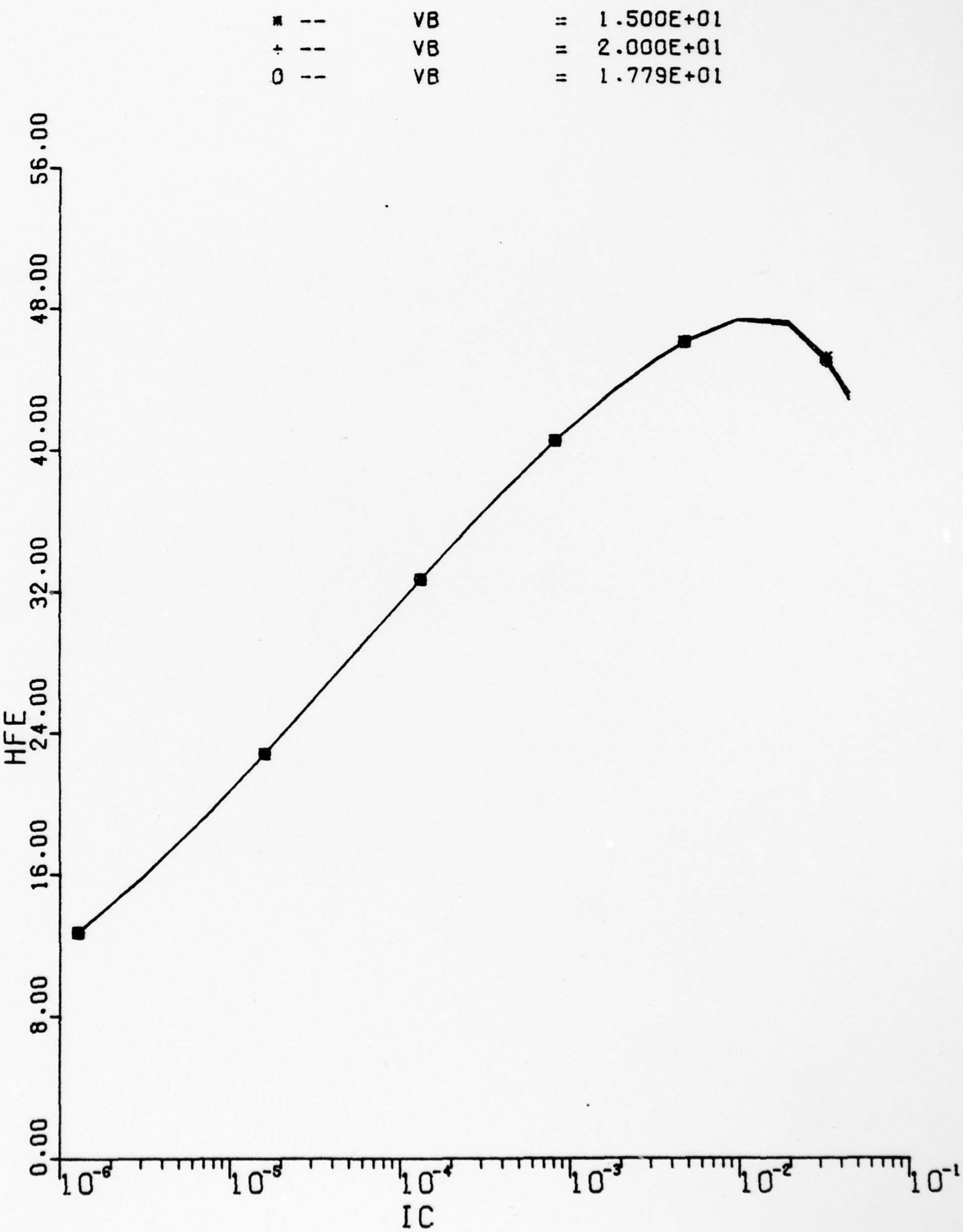
* -- M = 1.000E+00
+ -- M = 1.000E+01
0 -- M = 2.000E+00
HFE
0.00
8.00
16.00
24.00
32.00
40.00
48.00
56.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$



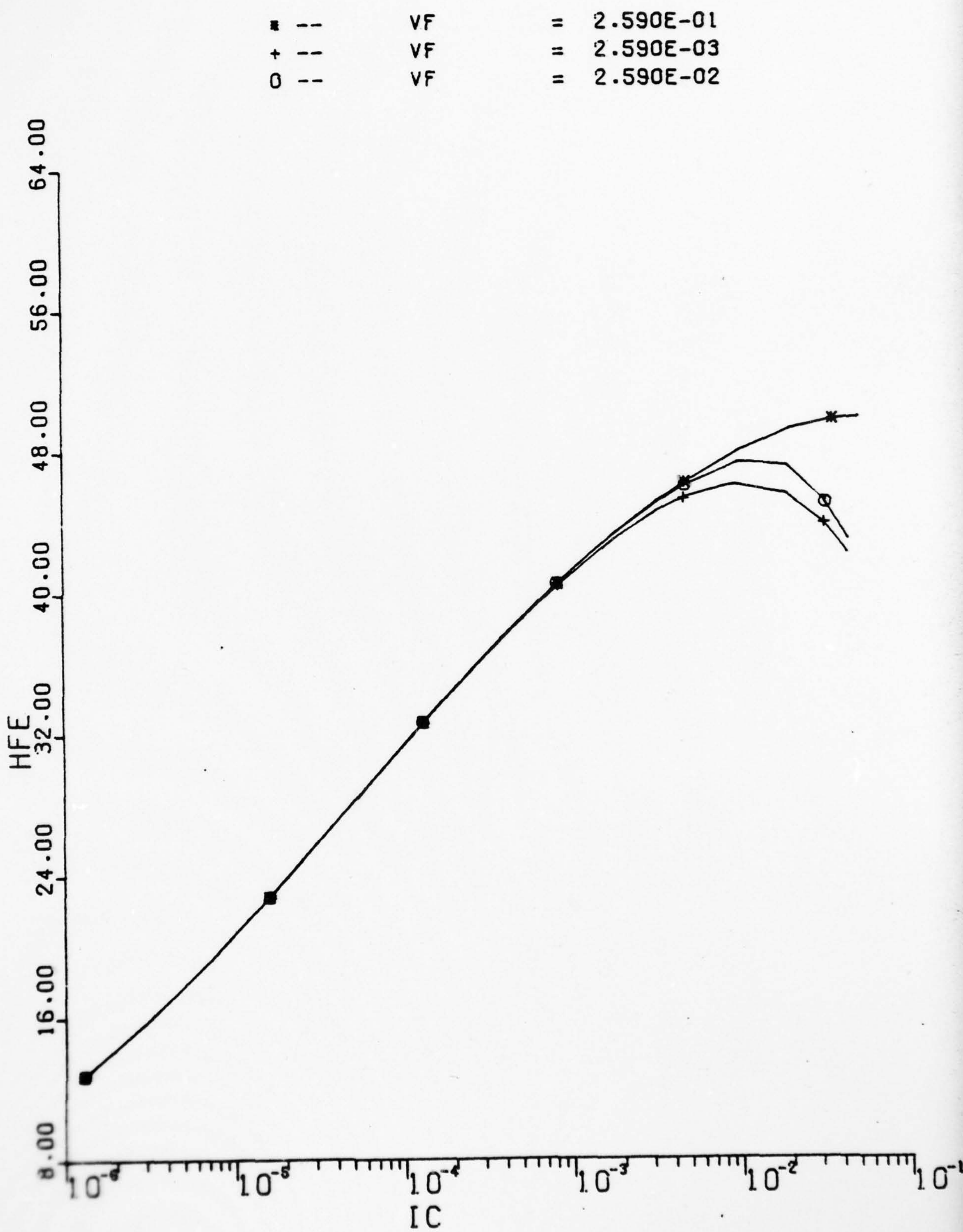
* -- NE = 8.000E-01
+ -- NE = 2.300E+00
O -- NE = 1.500E+00
HFE
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
IC



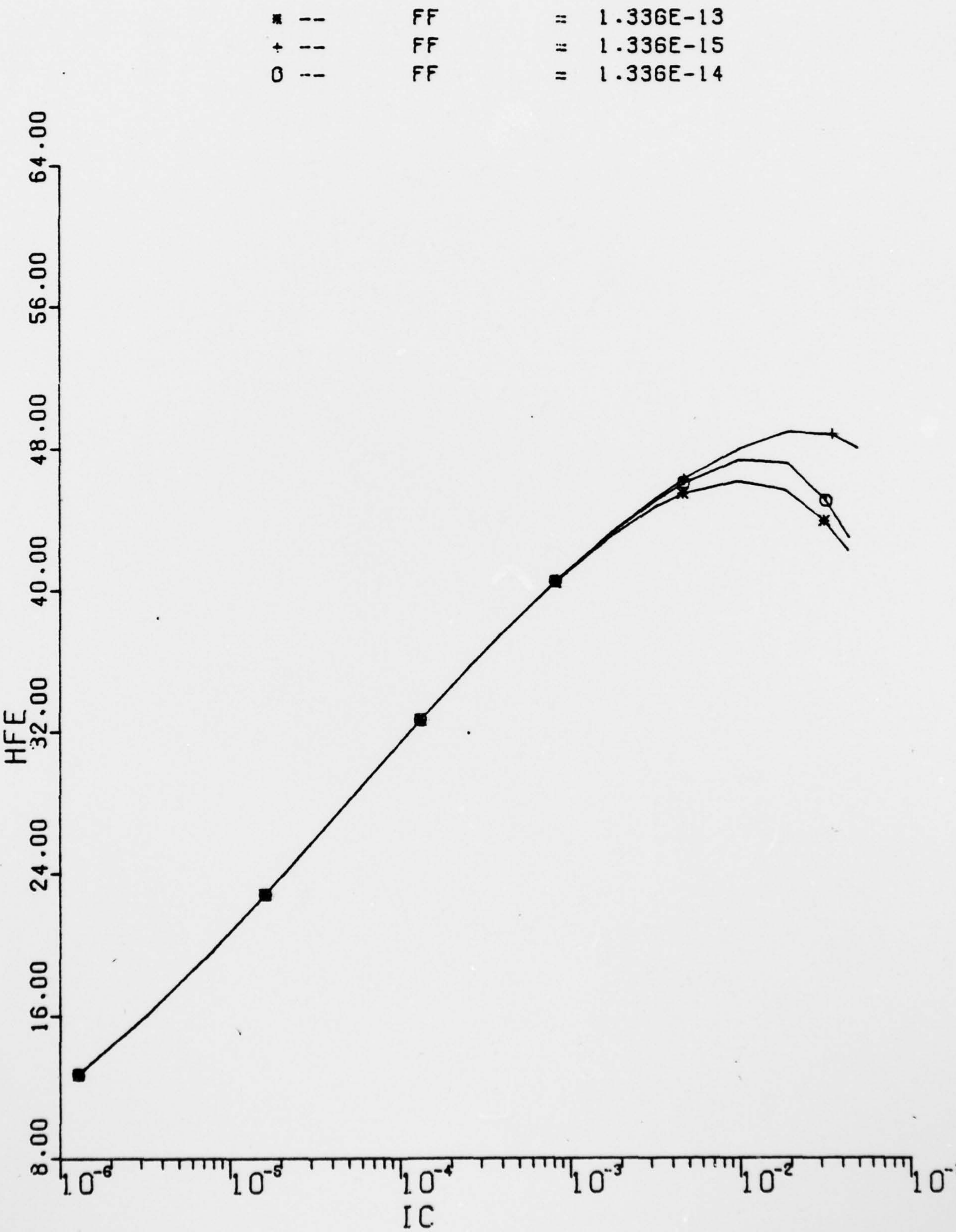
* -- VCE = 1.500E+00
+ -- VCE = 1.500E+01
0 -- VCE = 5.000E+00
HFE
64.00
56.00
48.00
40.00
32.00
24.00
16.00
8.00
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC



* -- VB = 1.500E+01
÷ -- VB = 2.000E+01
0 -- VB = 1.779E+01
56.00
48.00
40.00
32.00
24.00
HFE
16.00
8.00
0.00
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC

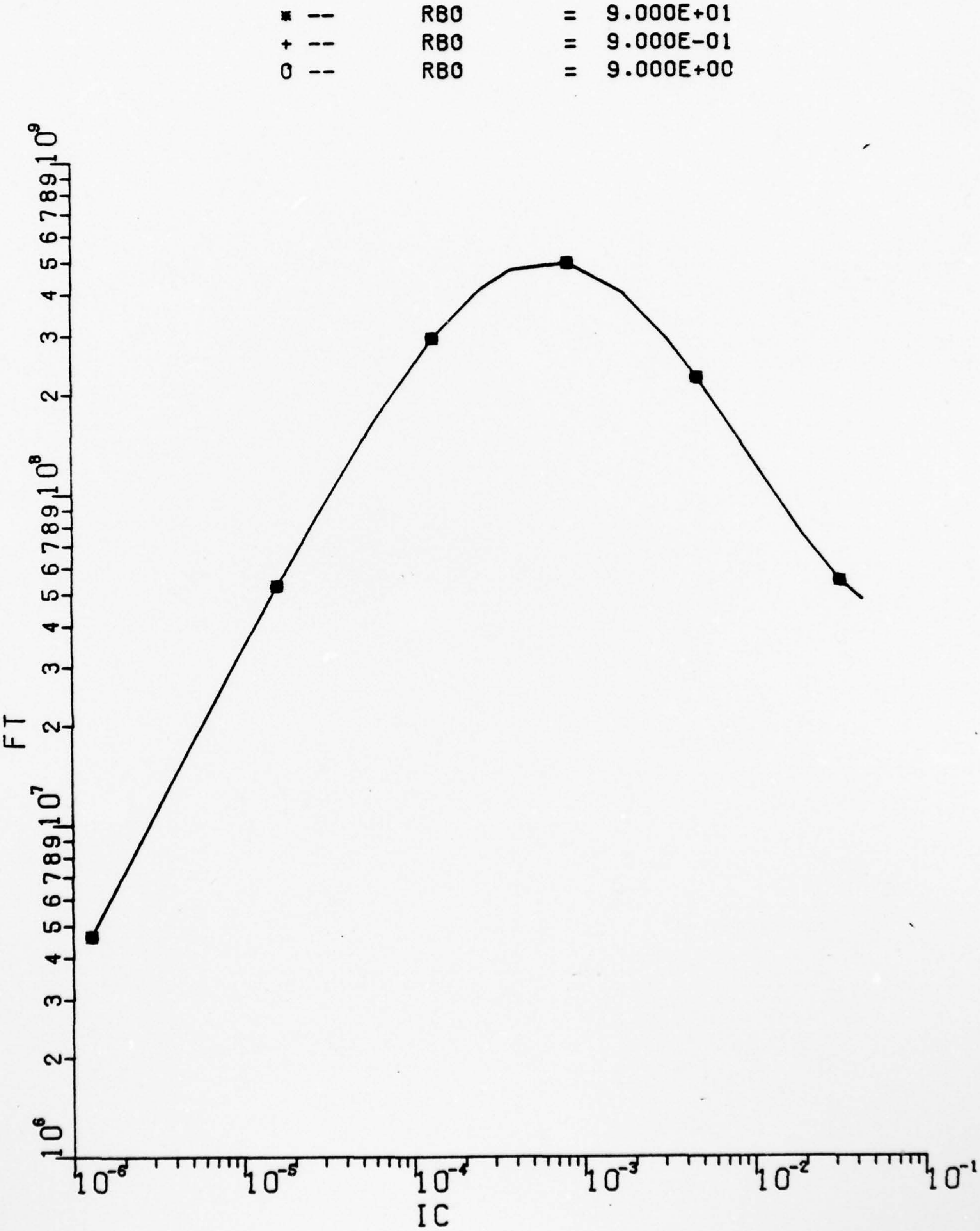


* -- VF = 2.590E-01
+ -- VF = 2.590E-03
0 -- VF = 2.590E-02
HFE
64.00
56.00
48.00
40.00
32.00
24.00
16.00
8.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

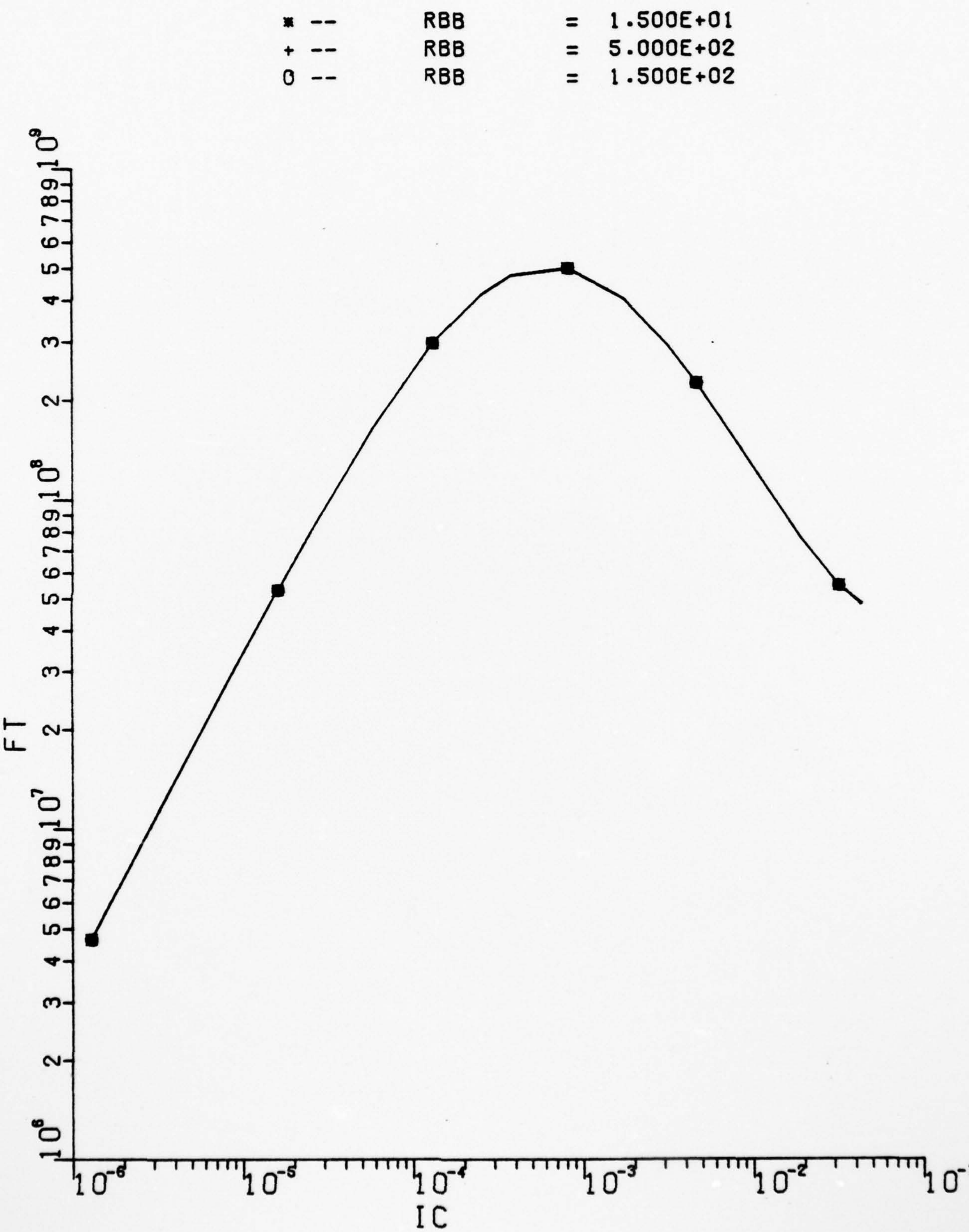


* -- FF = 1.336E-13
+ -- FF = 1.336E-15
O -- FF = 1.336E-14
HFE
64.00
56.00
48.00
40.00
32.00
24.00
16.00
8.00
IC
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

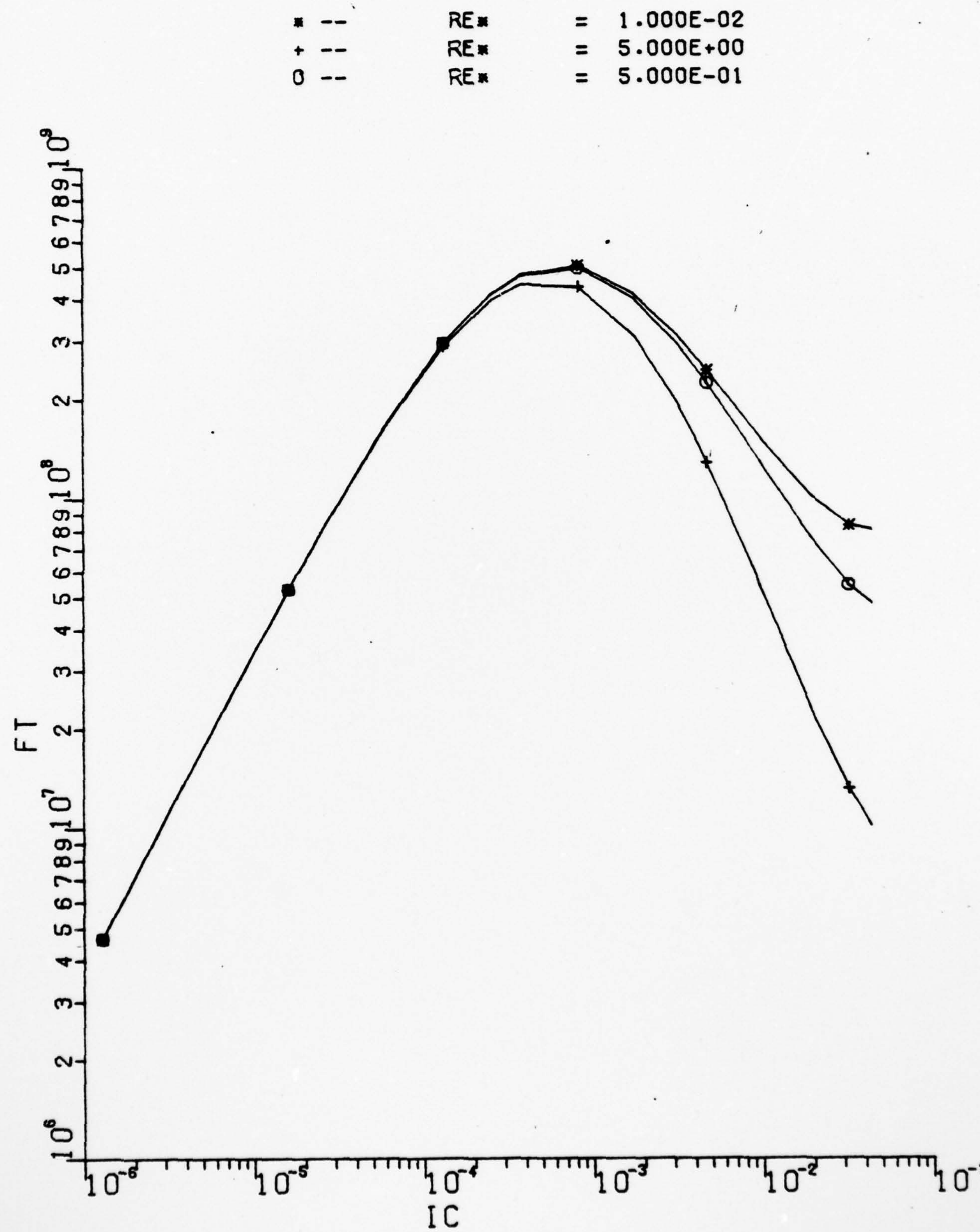
## B.4 $F_T$ vs. $I_c$ Curves



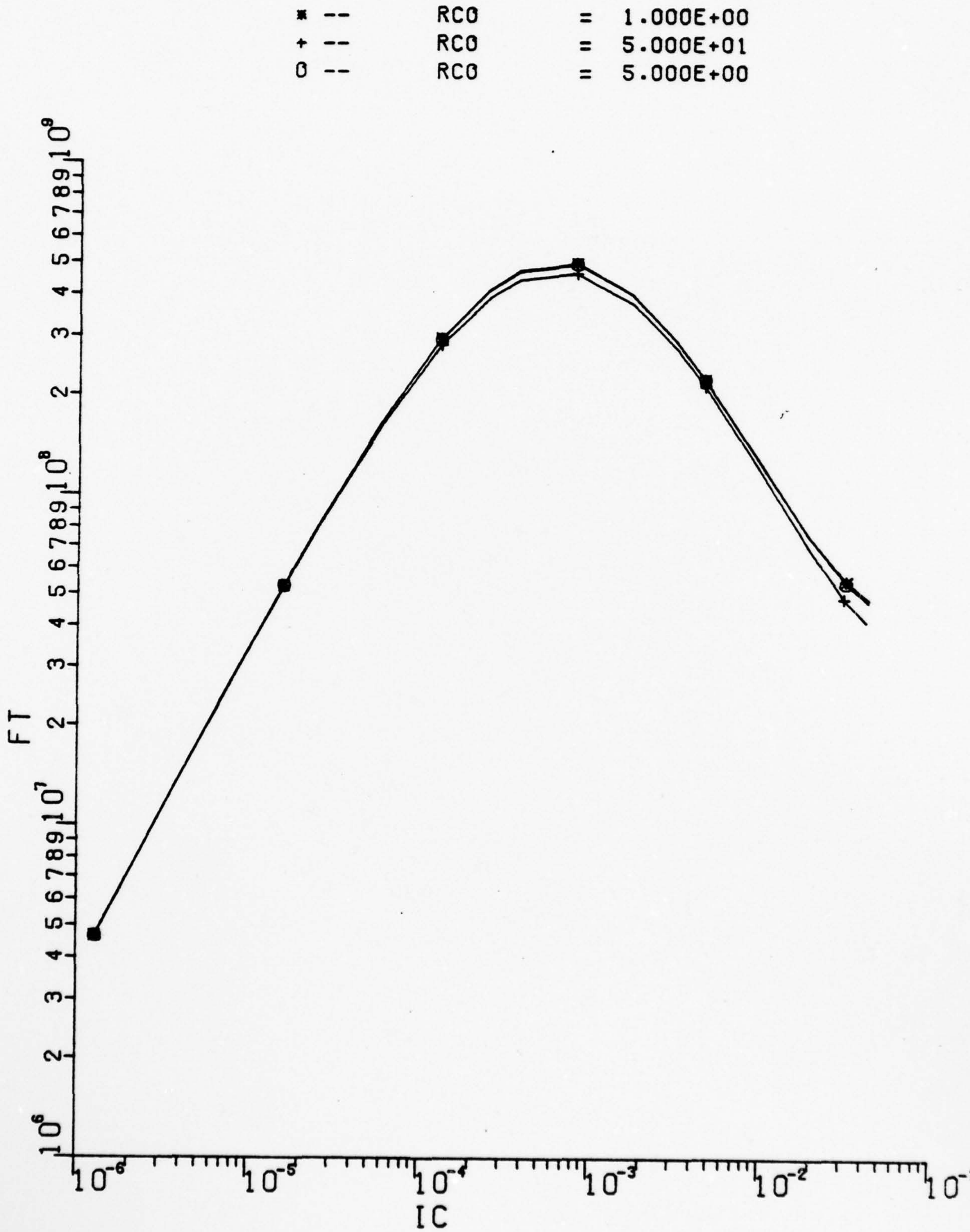
* -- RBO = 9.000E+01
+ -- RBO = 9.000E-01
0 -- RBO = 9.000E+00
FT
IC



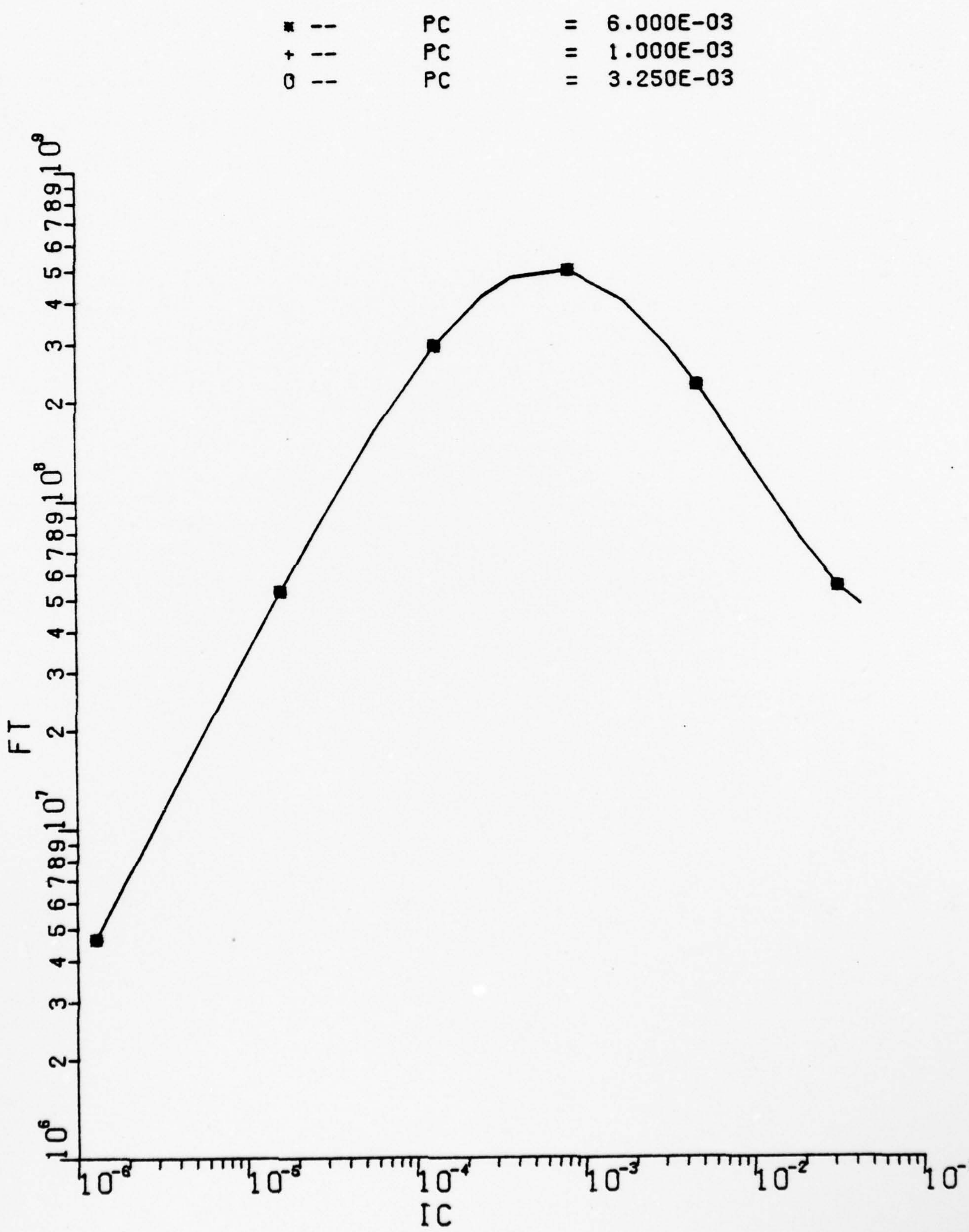
* -- RBB = 1.500E+01
+ -- RBB = 5.000E+02
0 -- RBB = 1.500E+02
FT
IC

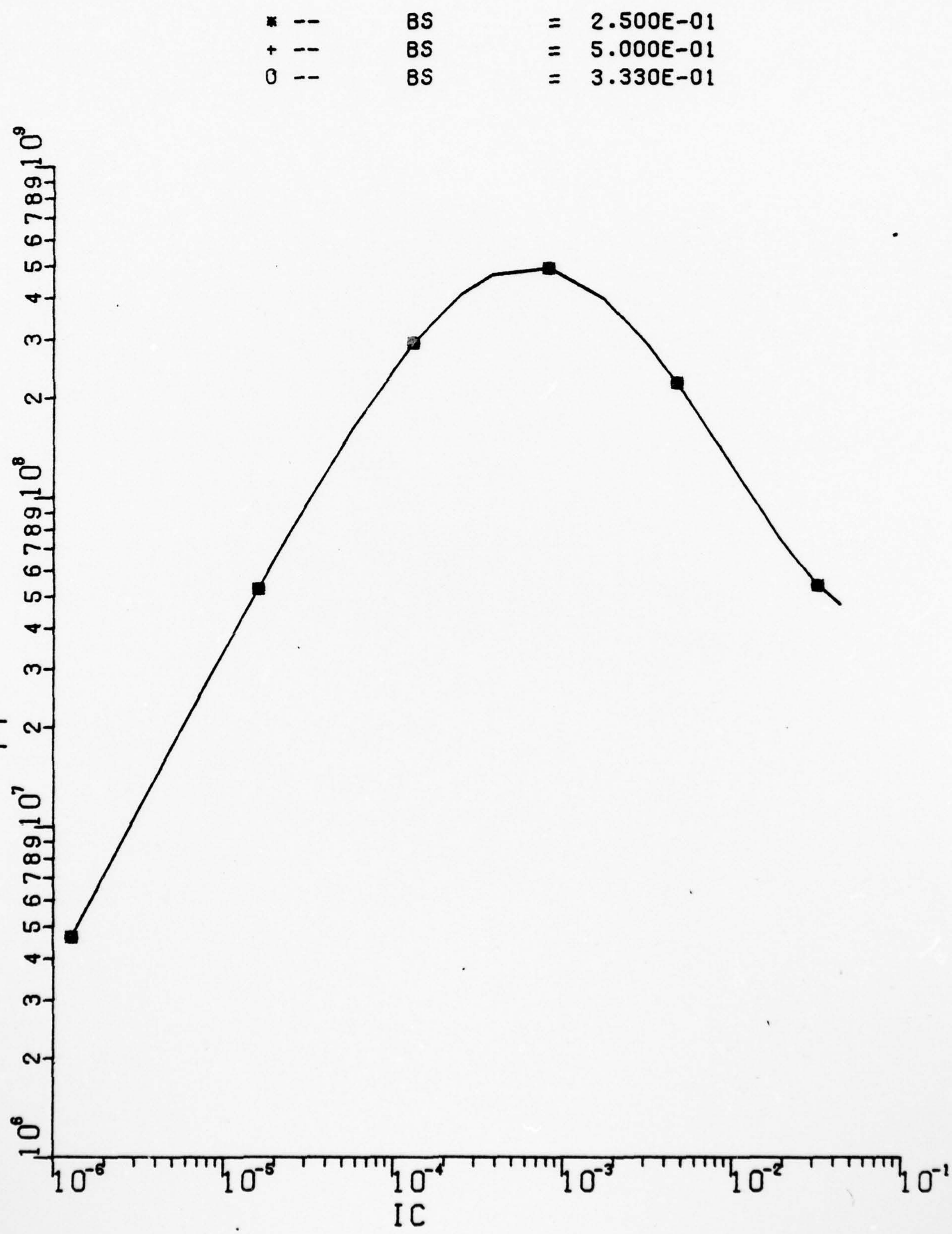


* -- RE* = 1.000E-02
+ -- RE* = 5.000E+00
O -- RE* = 5.000E-01
FT
IC

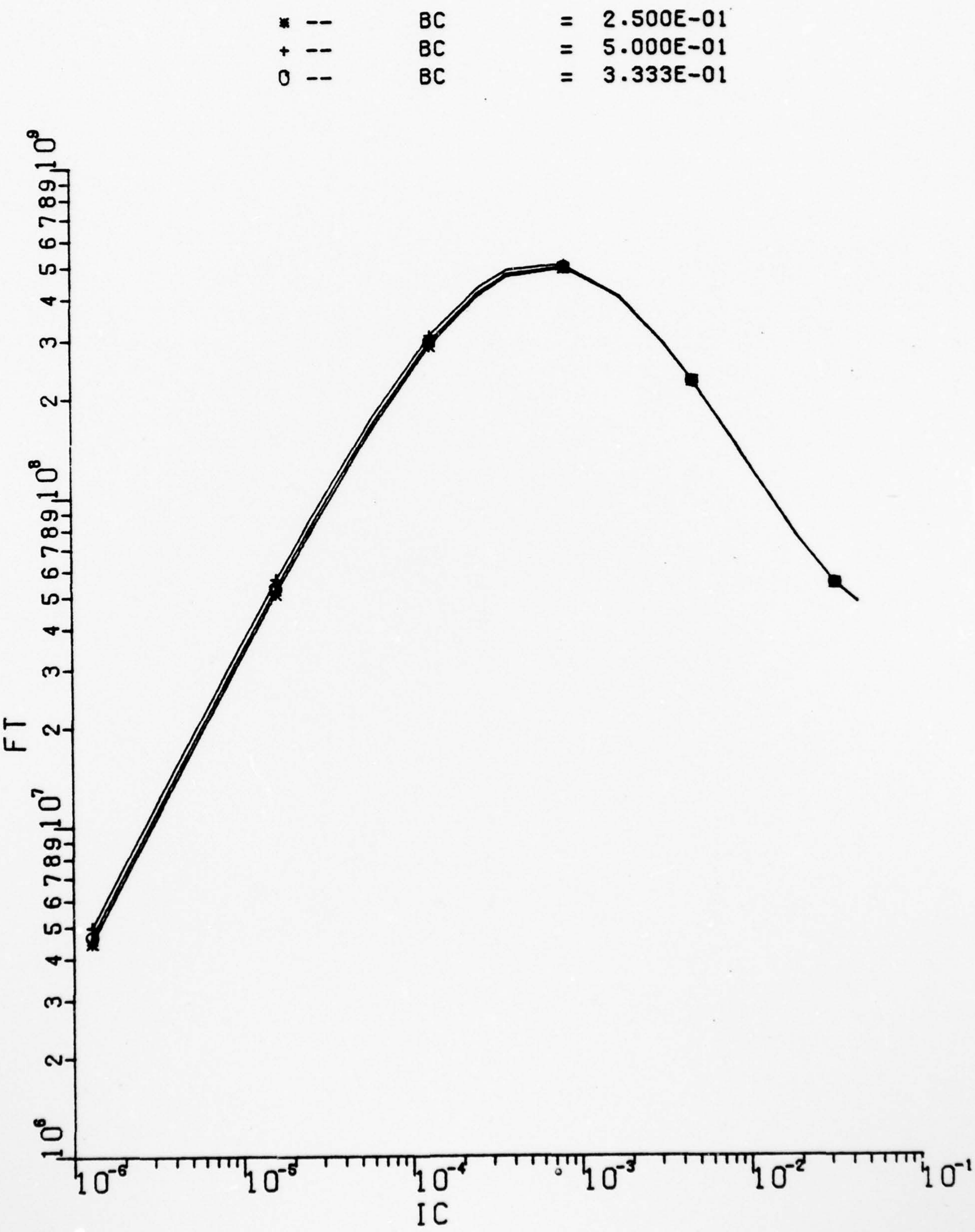


* -- RCO = 1.000E+00
+ -- RCO = 5.000E+01
O -- RCO = 5.000E+00
FT
IC

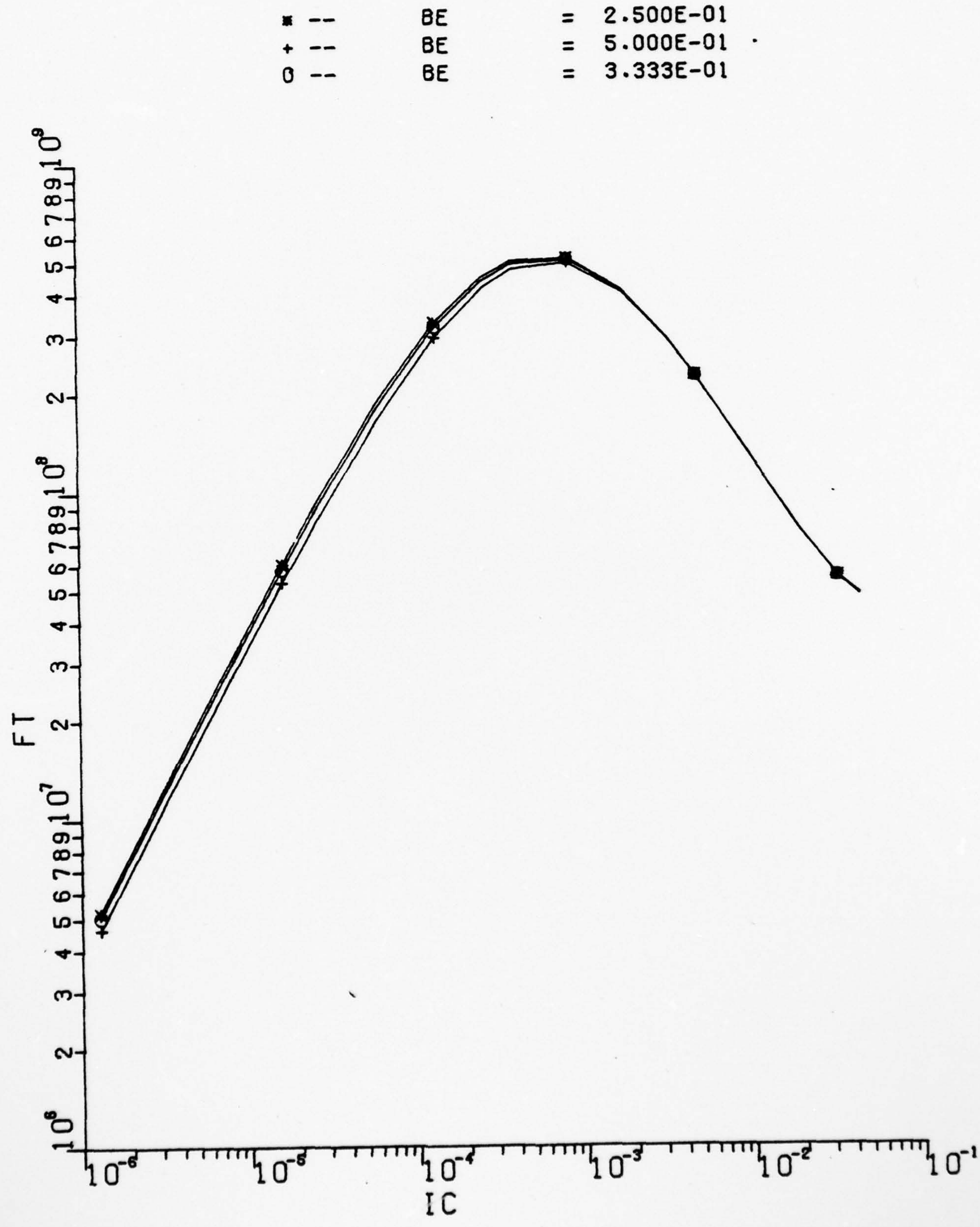

* -- PC = 6.000E-03
+ -- PC = 1.000E-03
O -- PC = 3.250E-03
FT
IC
$10^{6}$
$10^{7}$
$10^{8}$
$10^{9}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$



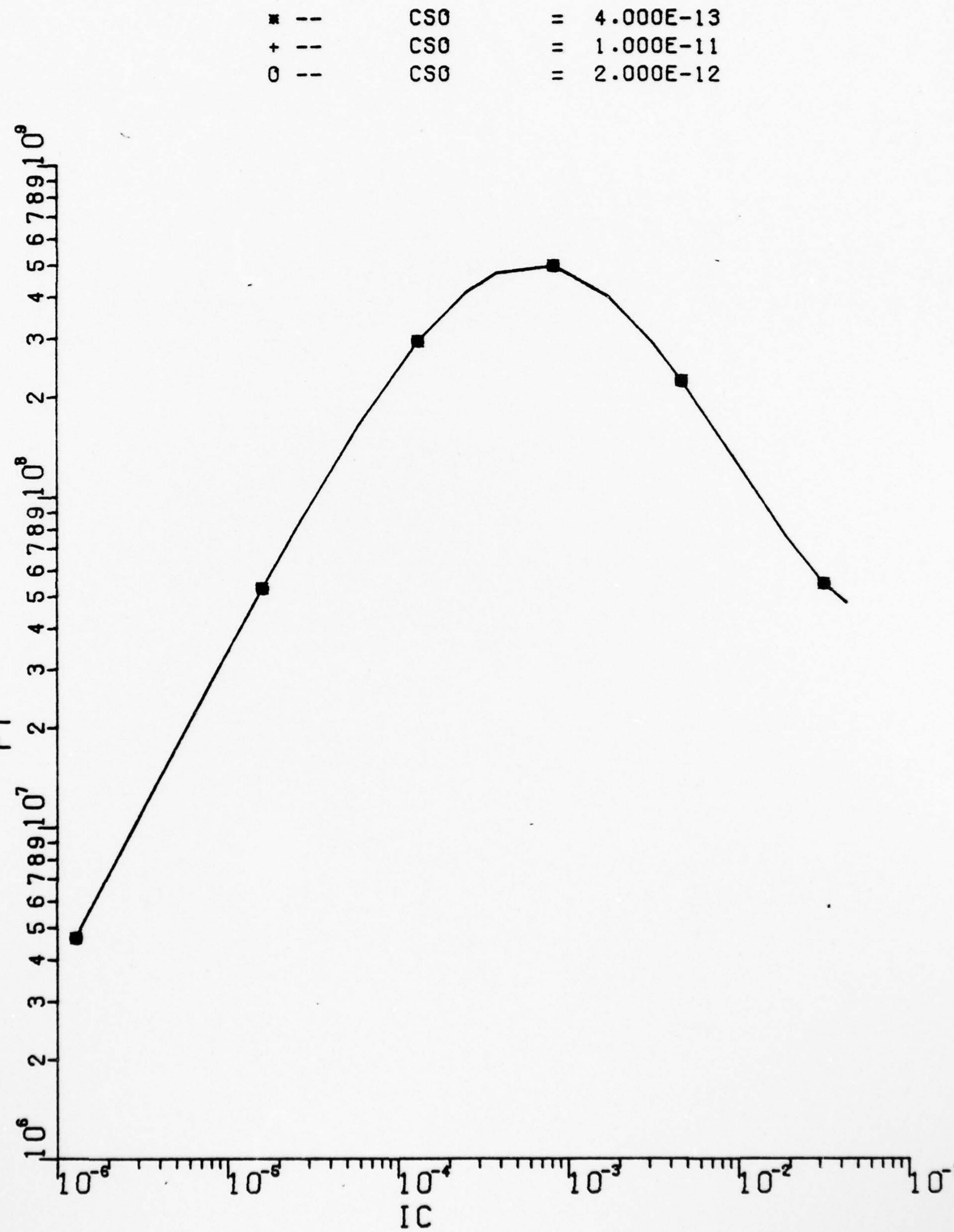
* -- BS = 2.500E-01
+ -- BS = 5.000E-01
0 -- BS = 3.330E-01
FT
IC



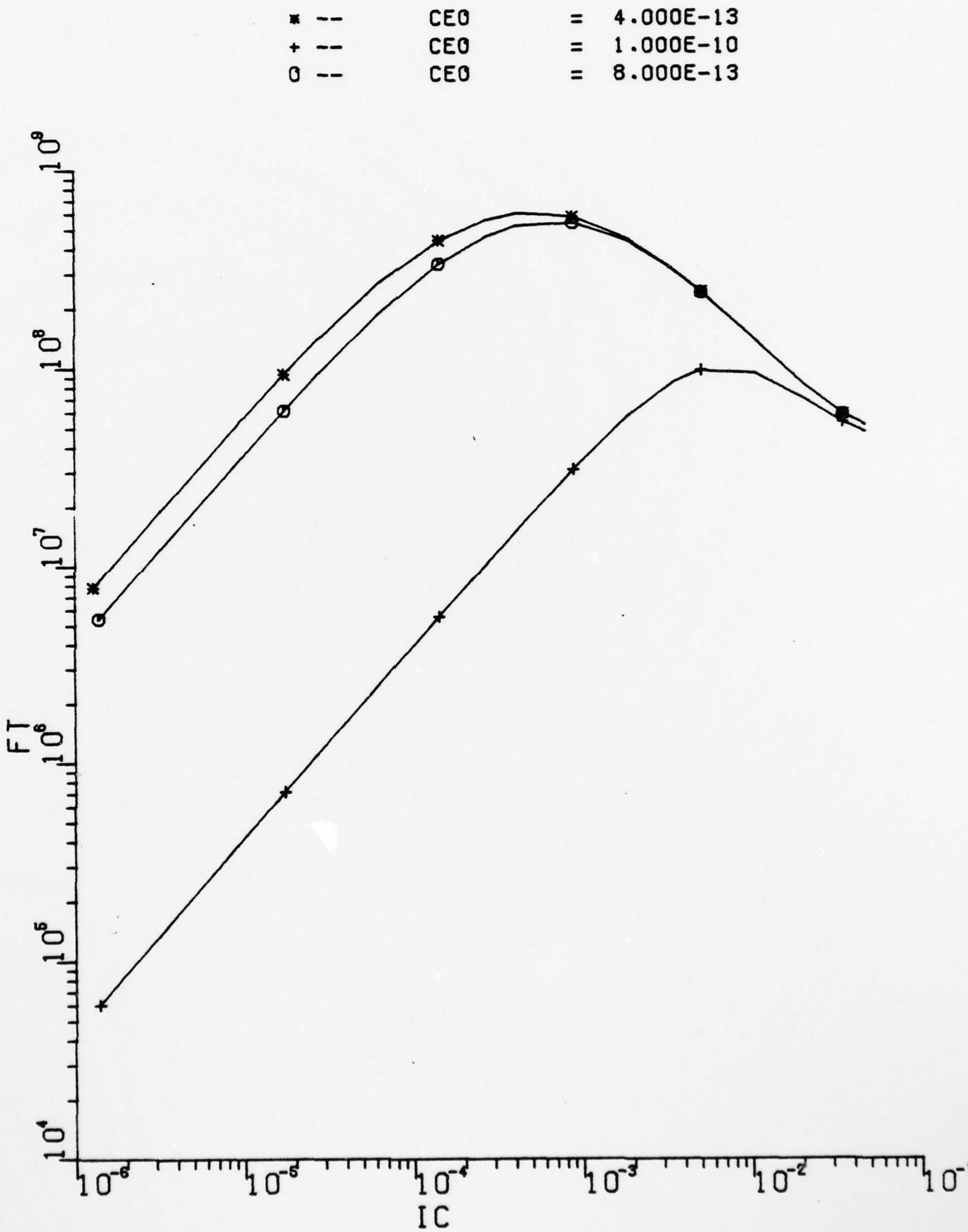
* -- BC = 2.500E-01
+ -- BC = 5.000E-01
O -- BC = 3.333E-01
FT
IC

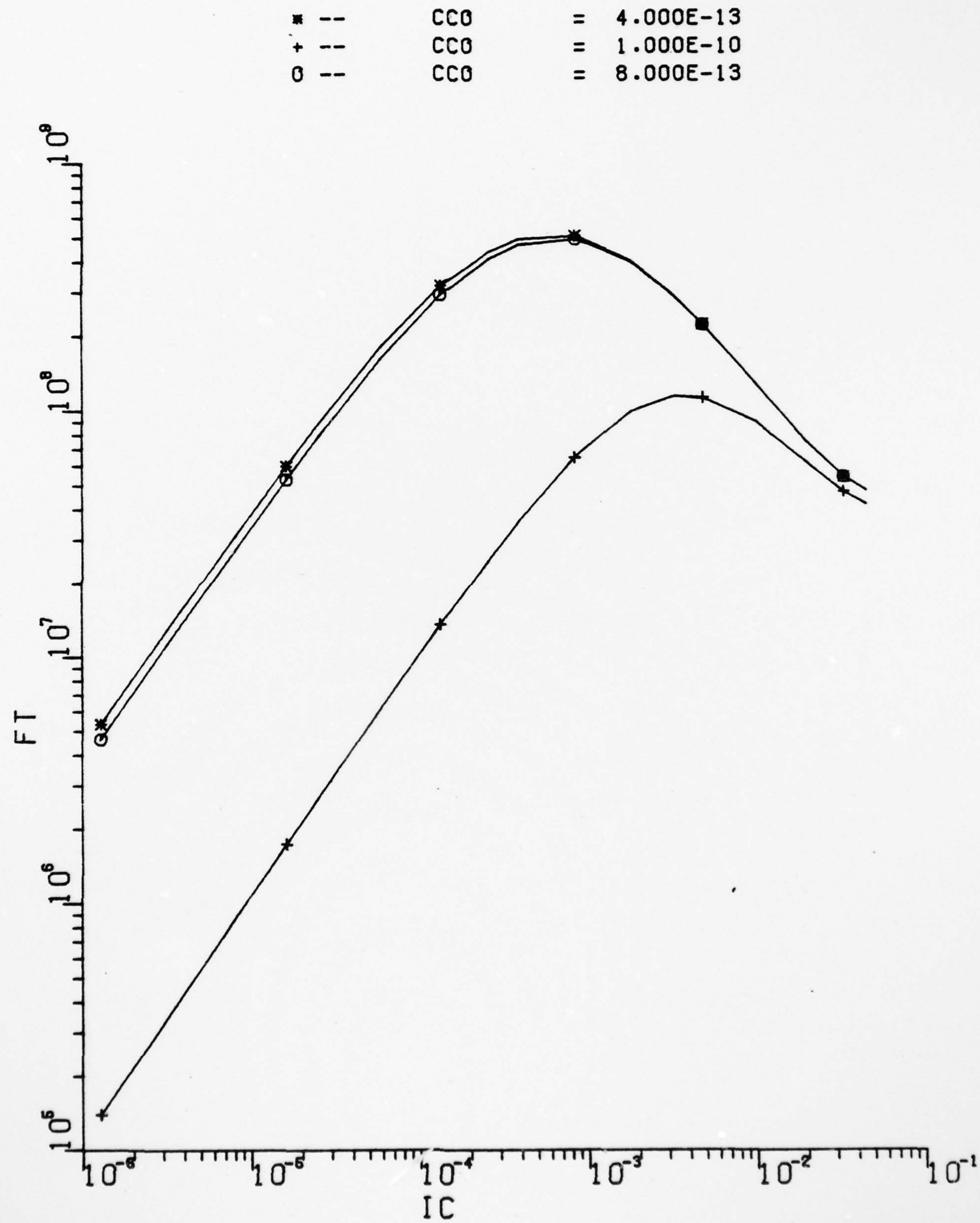


* -- BE = 2.500E-01
+ -- BE = 5.000E-01
0 -- BE = 3.333E-01
FT
IC



* -- CSO = 4.000E-13
+ -- CSO = 1.000E-11
O -- CSO = 2.000E-12
FT
IC

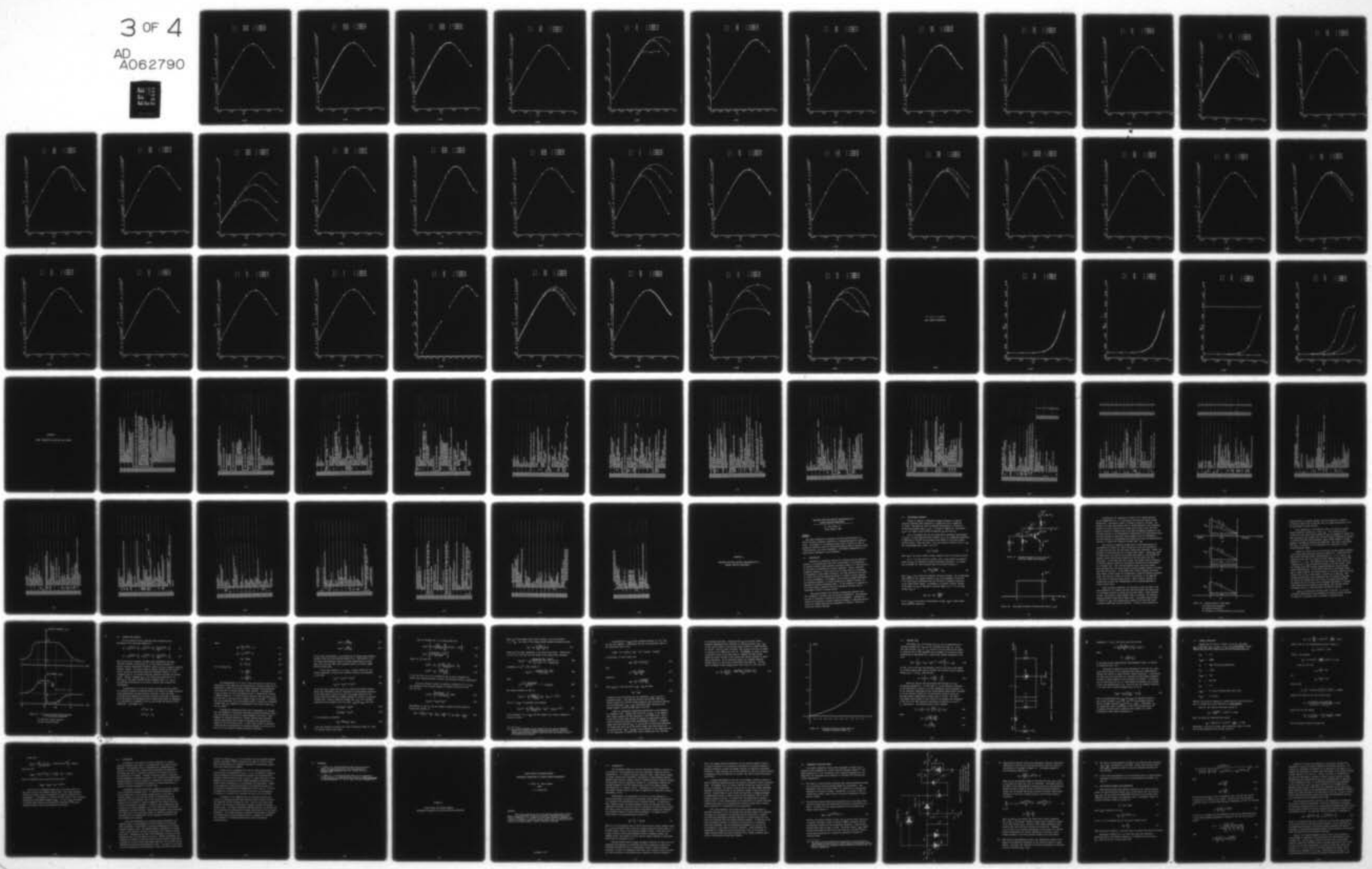

* -- CEO = 4.000E-13
+ -- CEO = 1.000E-10
O -- CEO = 8.000E-13
FT
IC
10^4
10^5
10^6
10^7
10^8
10^9
10^-6
10^-5
10^-4
10^-3
10^-2
10^-1

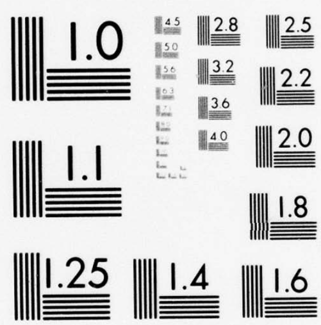


* -- CCO = 4.000E-13
+ -- CCO = 1.000E-10
O -- CCO = 8.000E-13
FT
IC

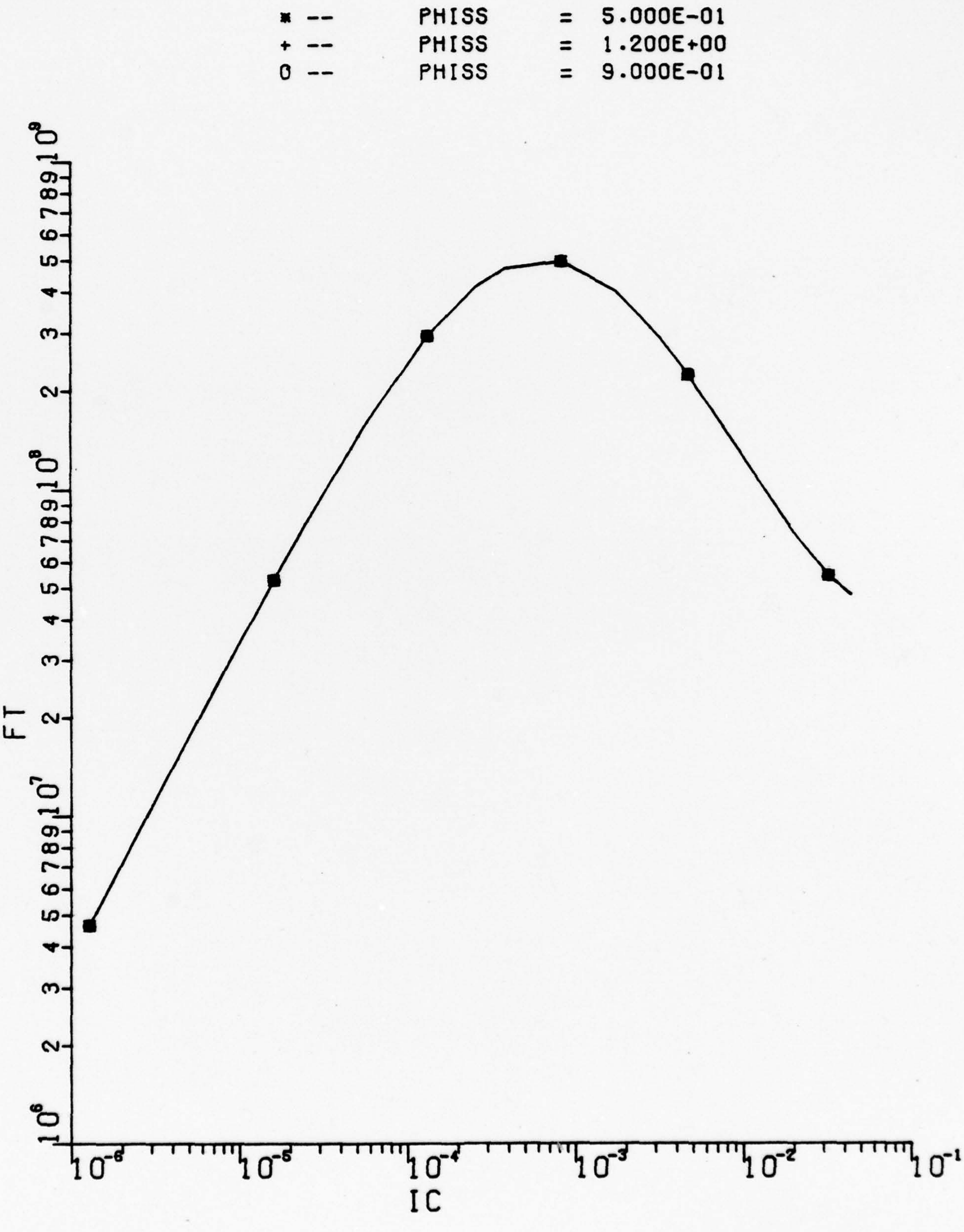
AD-A062 790 TRW DEFENSE AND SPACE SYSTEMS GROUP REDONDO BEACH CALIF F/G 9/1
PROCESS-ORIENTED, HIGH-INJECTION CIRCUIT MODELS FOR INTEGRATED --ETC(U)
JAN 78 J CHOMA N00014-77-C-0043
UNCLASSIFIED TRW-78.4734.7-023-PT-2-VO NL

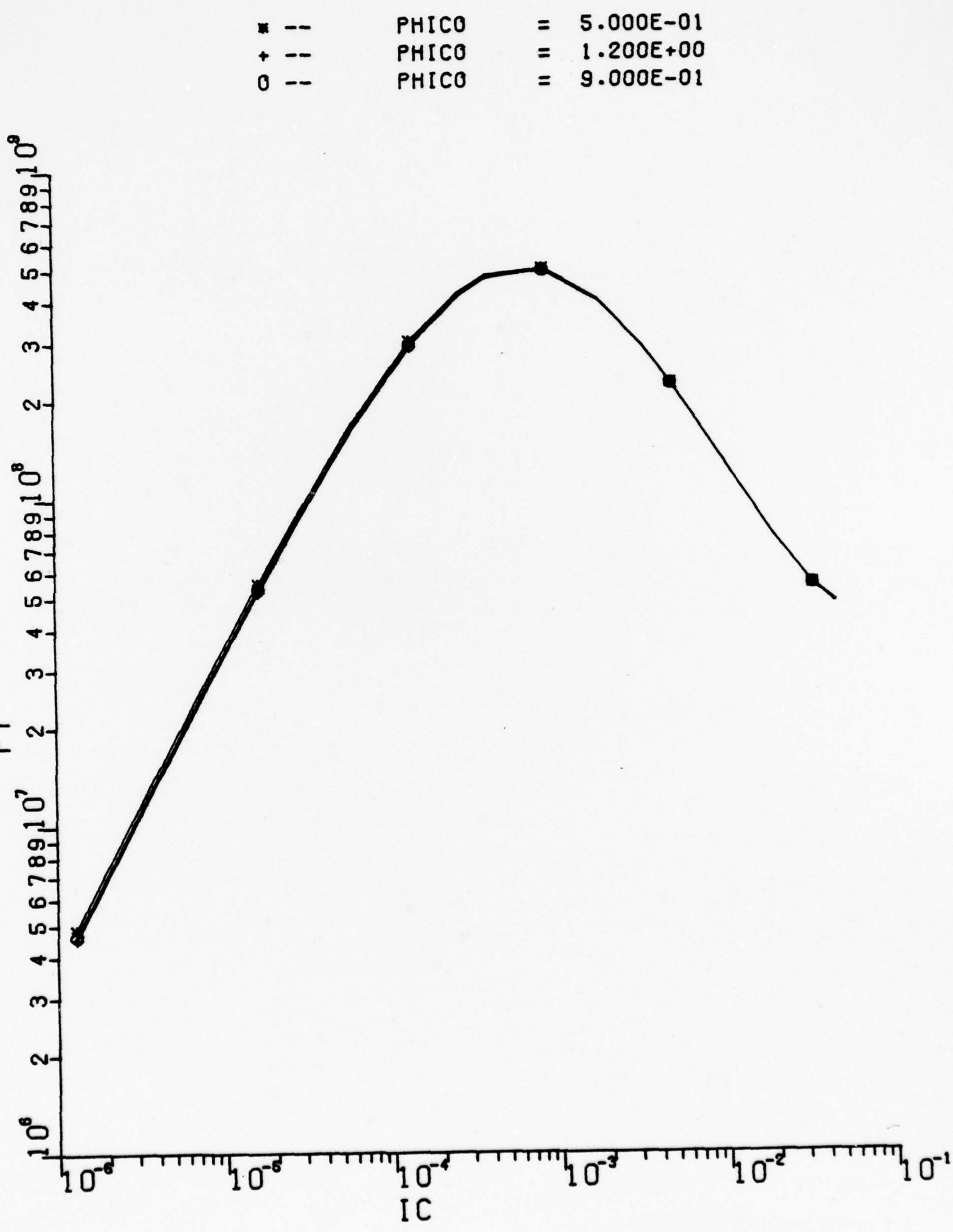
3 OF 4
AD A062790



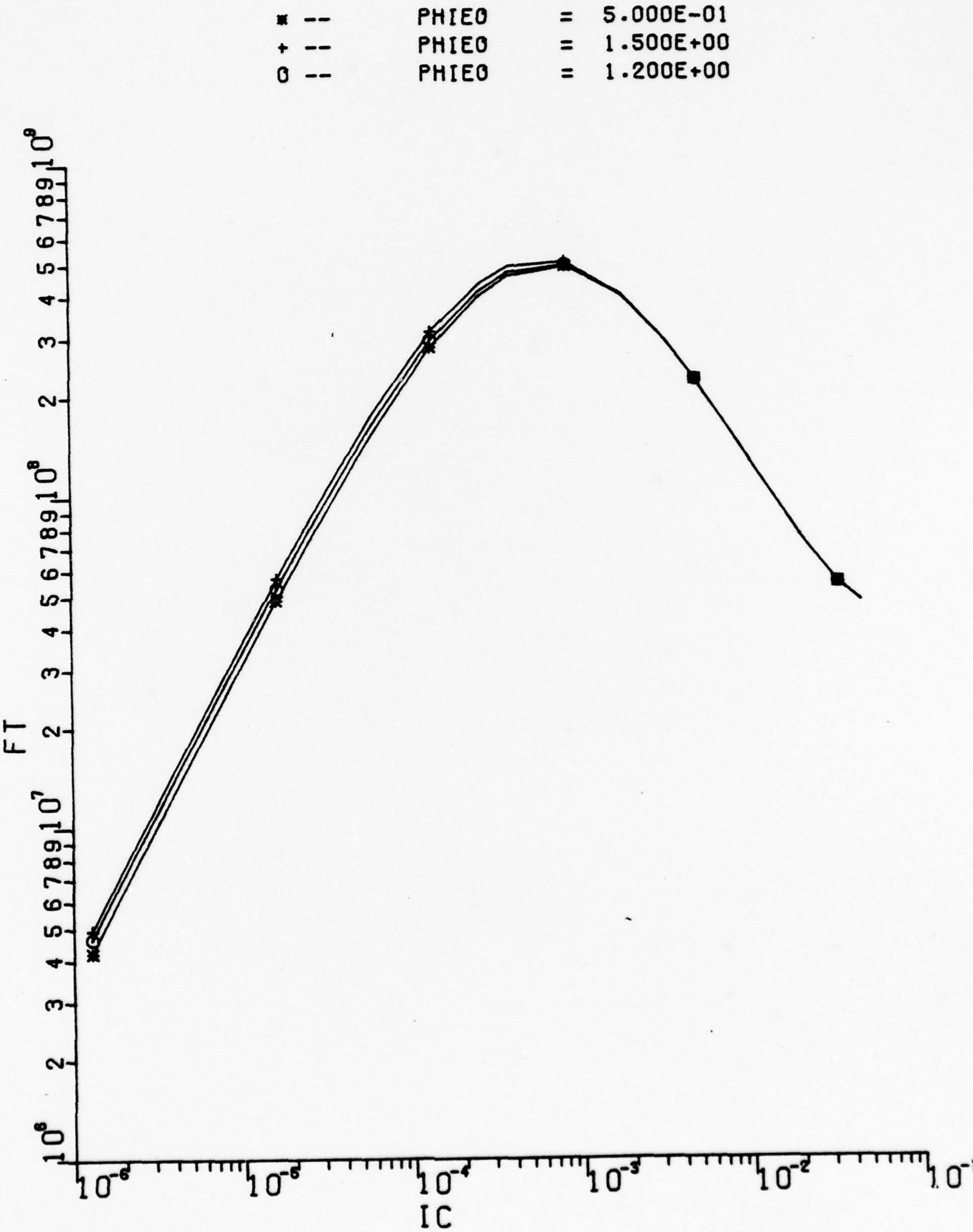



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

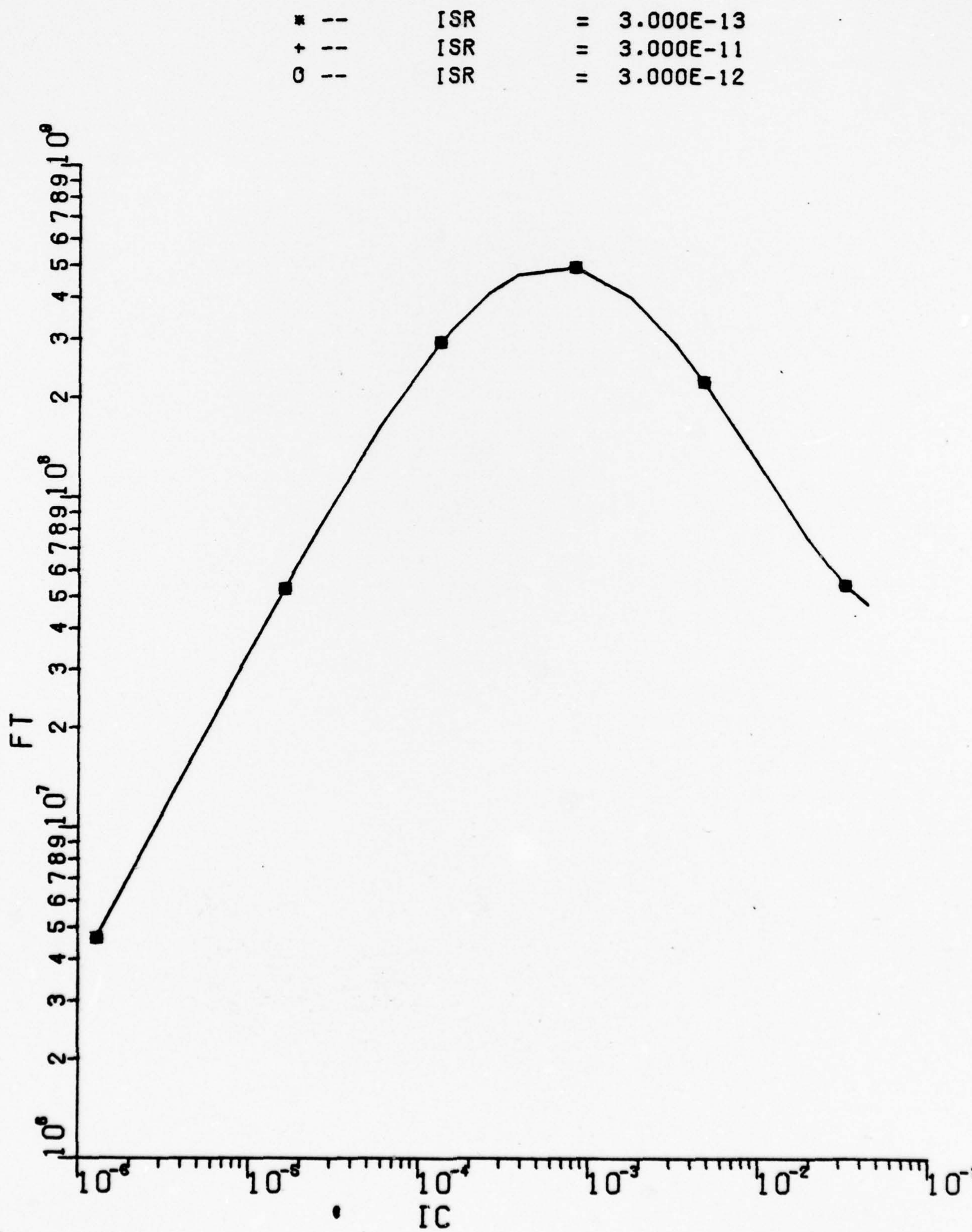

* -- PHISS = 5.000E-01
+ -- PHISS = 1.200E+00
O -- PHISS = 9.000E-01
FT
IC
$10^{6}$
$10^{7}$
$10^{8}$
$10^{9}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$



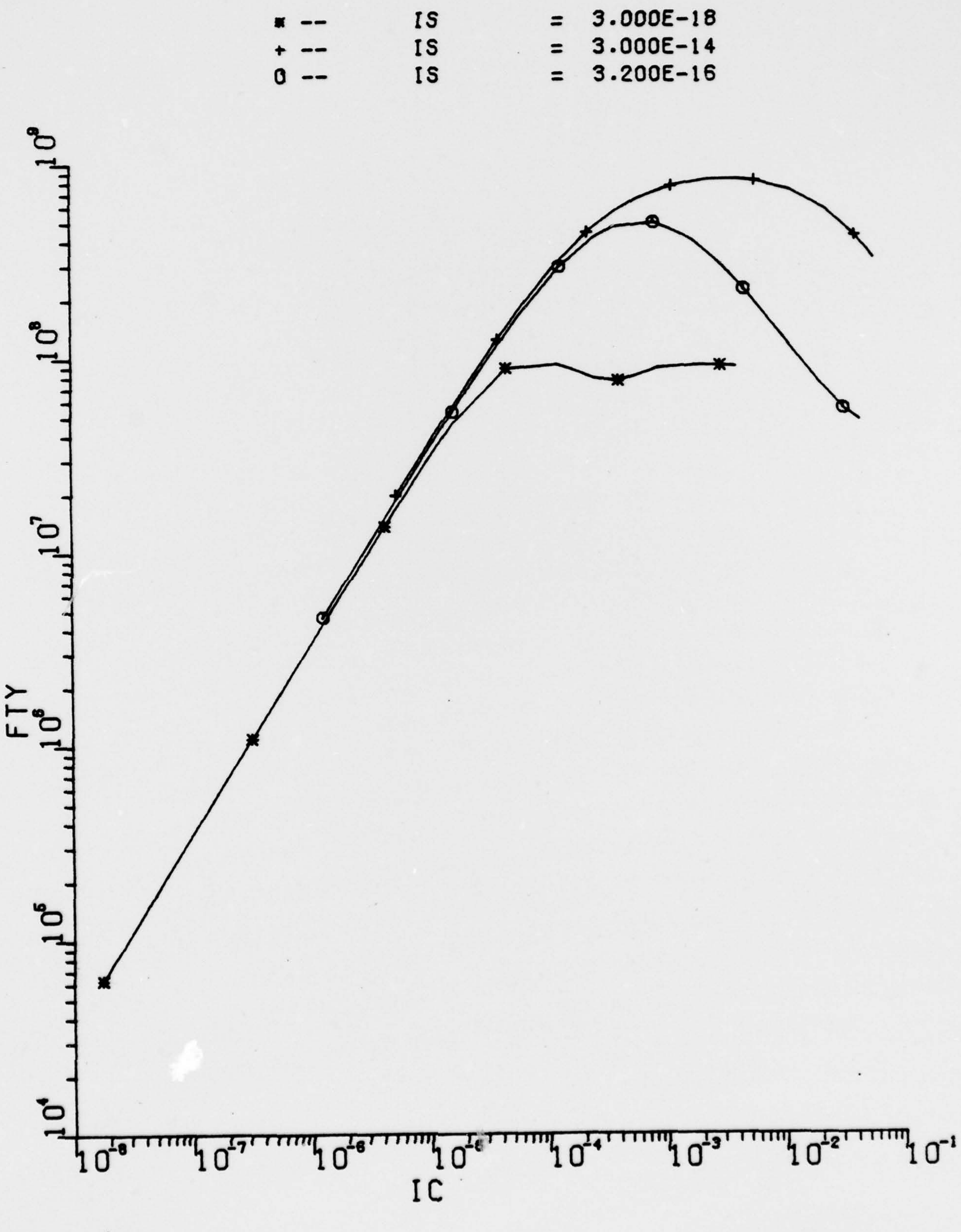
* -- PHICO = 5.000E-01
+ -- PHICO = 1.200E+00
0 -- PHICO = 9.000E-01
FT
IC



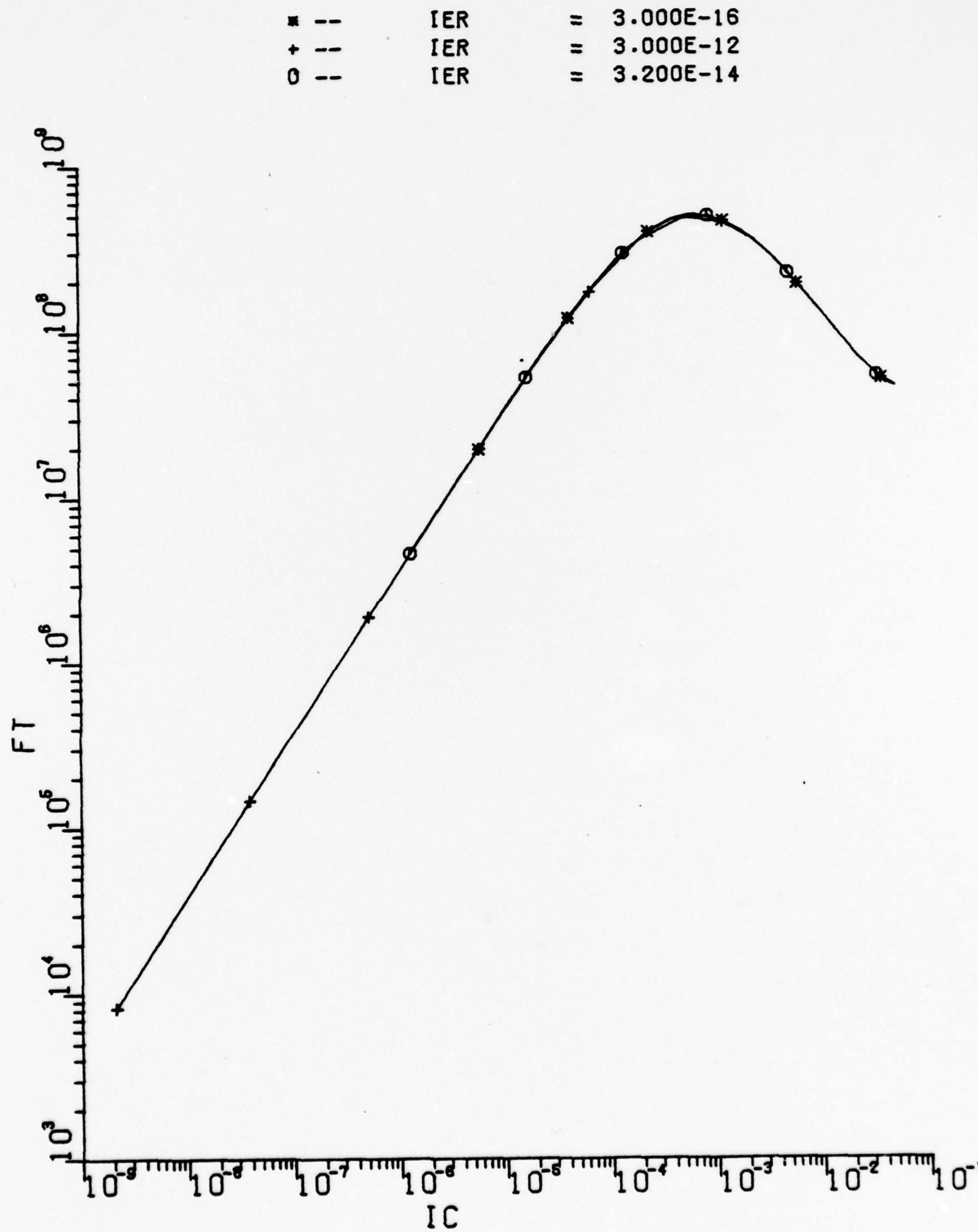
* -- PHIEO = 5.000E-01
+ -- PHIEO = 1.500E+00
O -- PHIEO = 1.200E+00
FT
IC



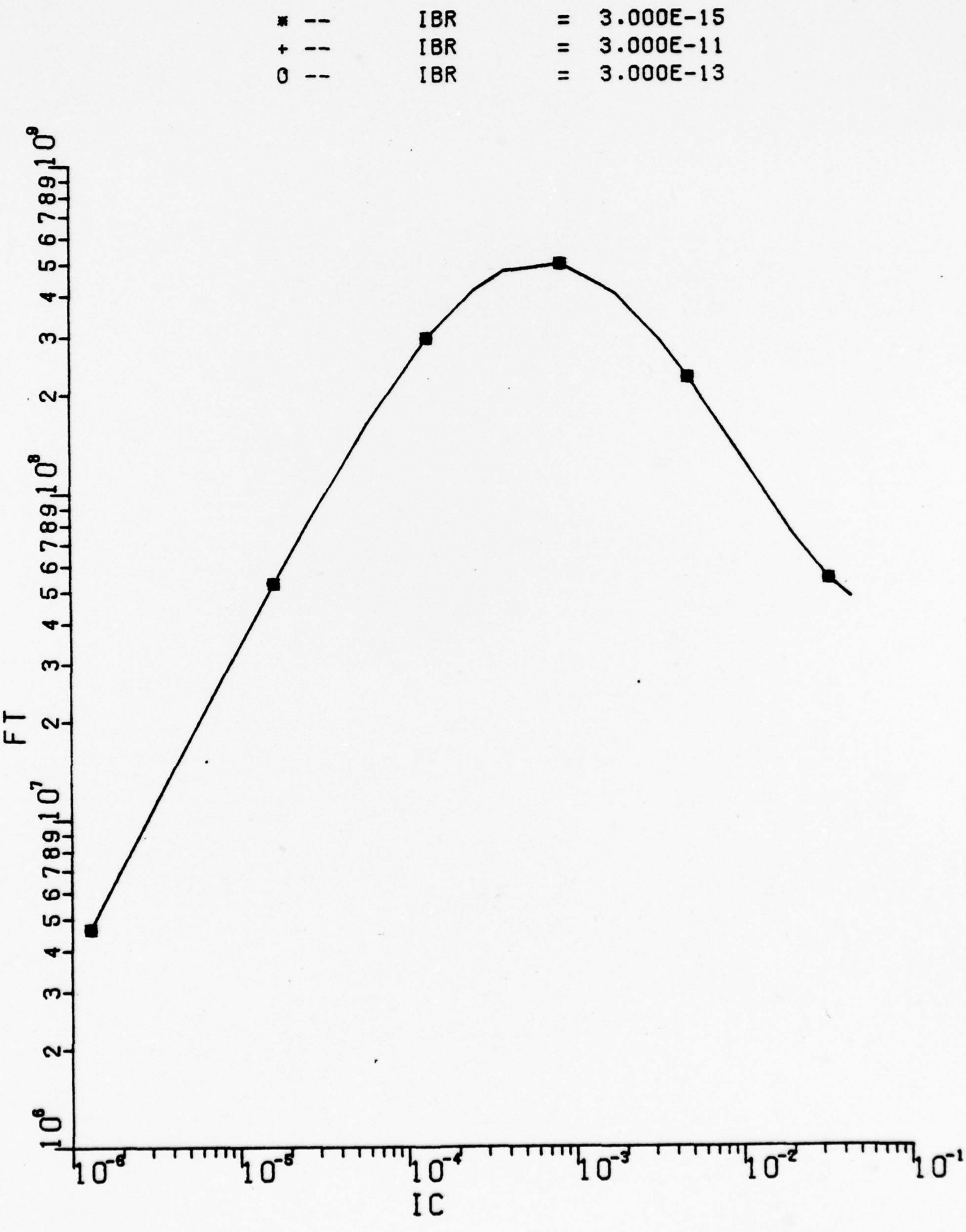
* -- ISR = 3.000E-13
+ -- ISR = 3.000E-11
O -- ISR = 3.000E-12
FT
IC



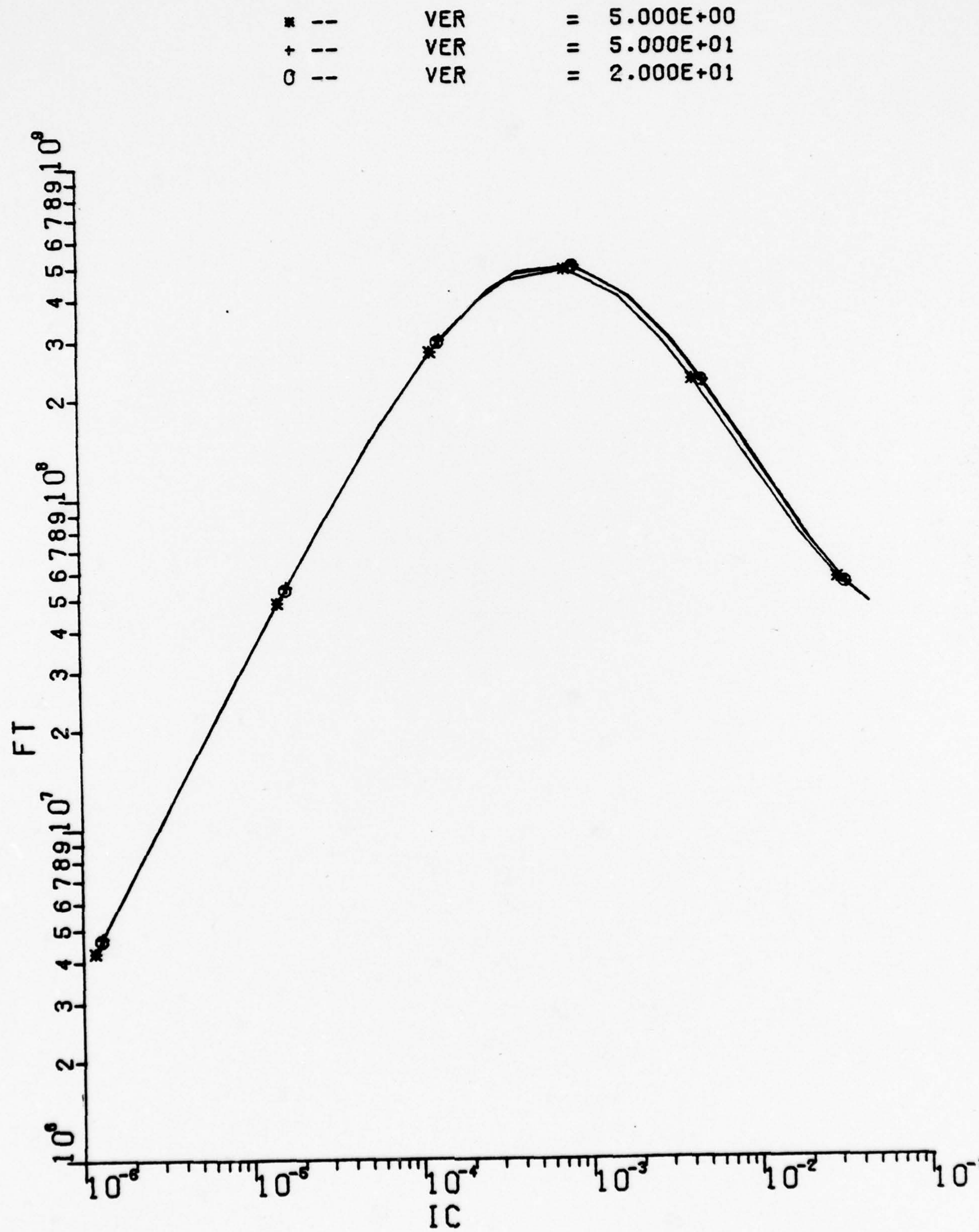
* -- IS = 3.000E-18
+ -- IS = 3.000E-14
O -- IS = 3.200E-16
FTY
IC



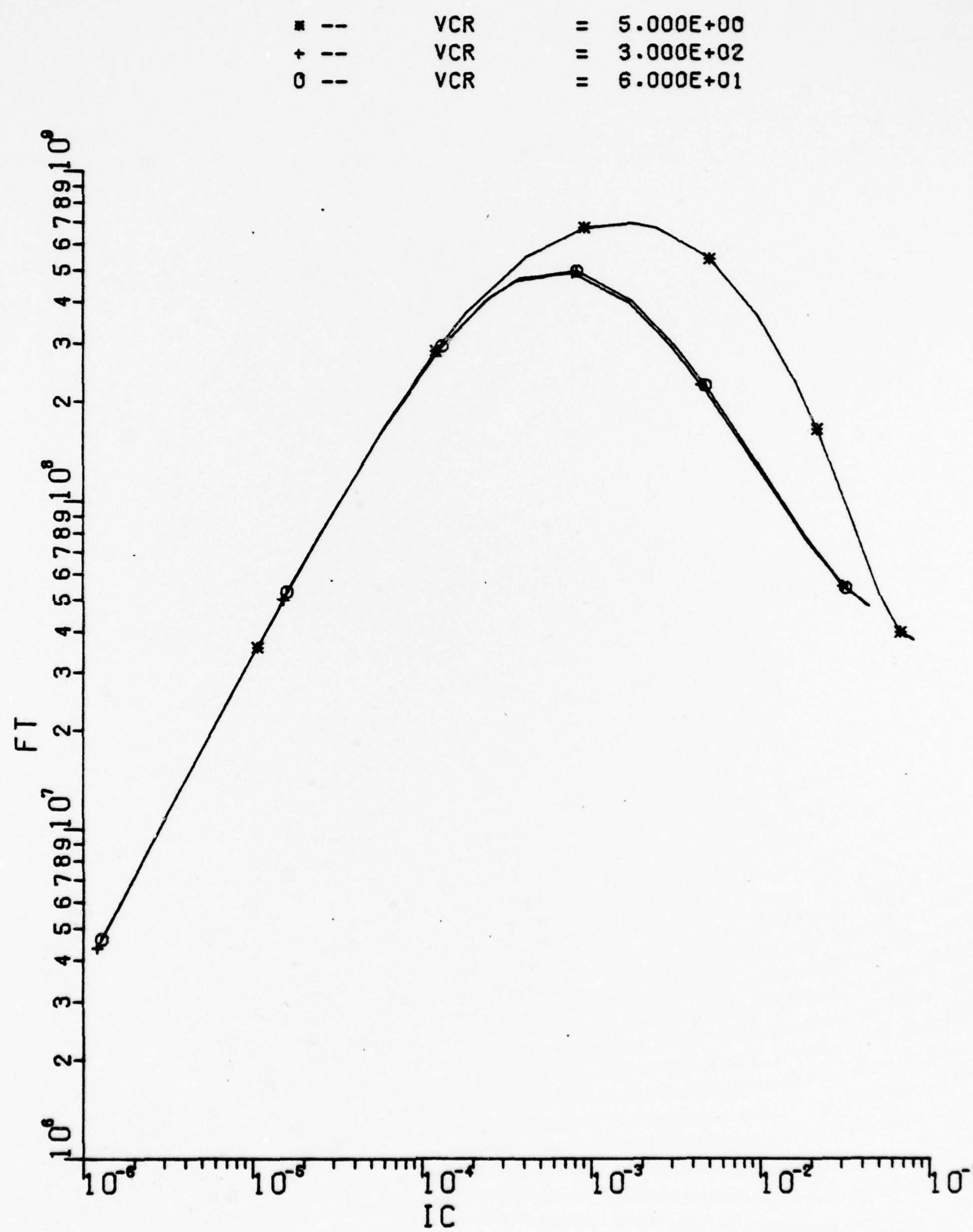
* -- IER = 3.000E-16
+ -- IER = 3.000E-12
0 -- IER = 3.200E-14
FT
IC

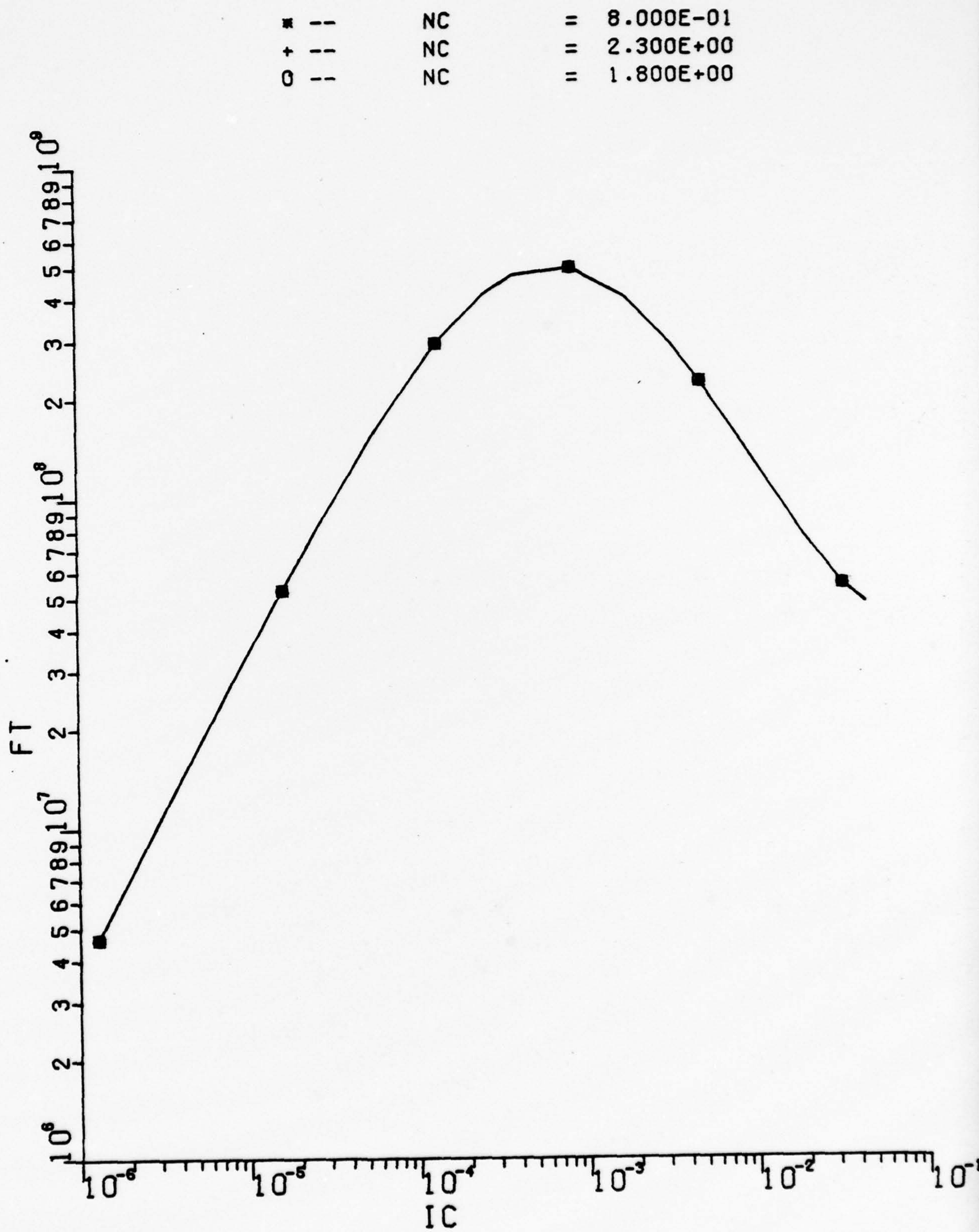


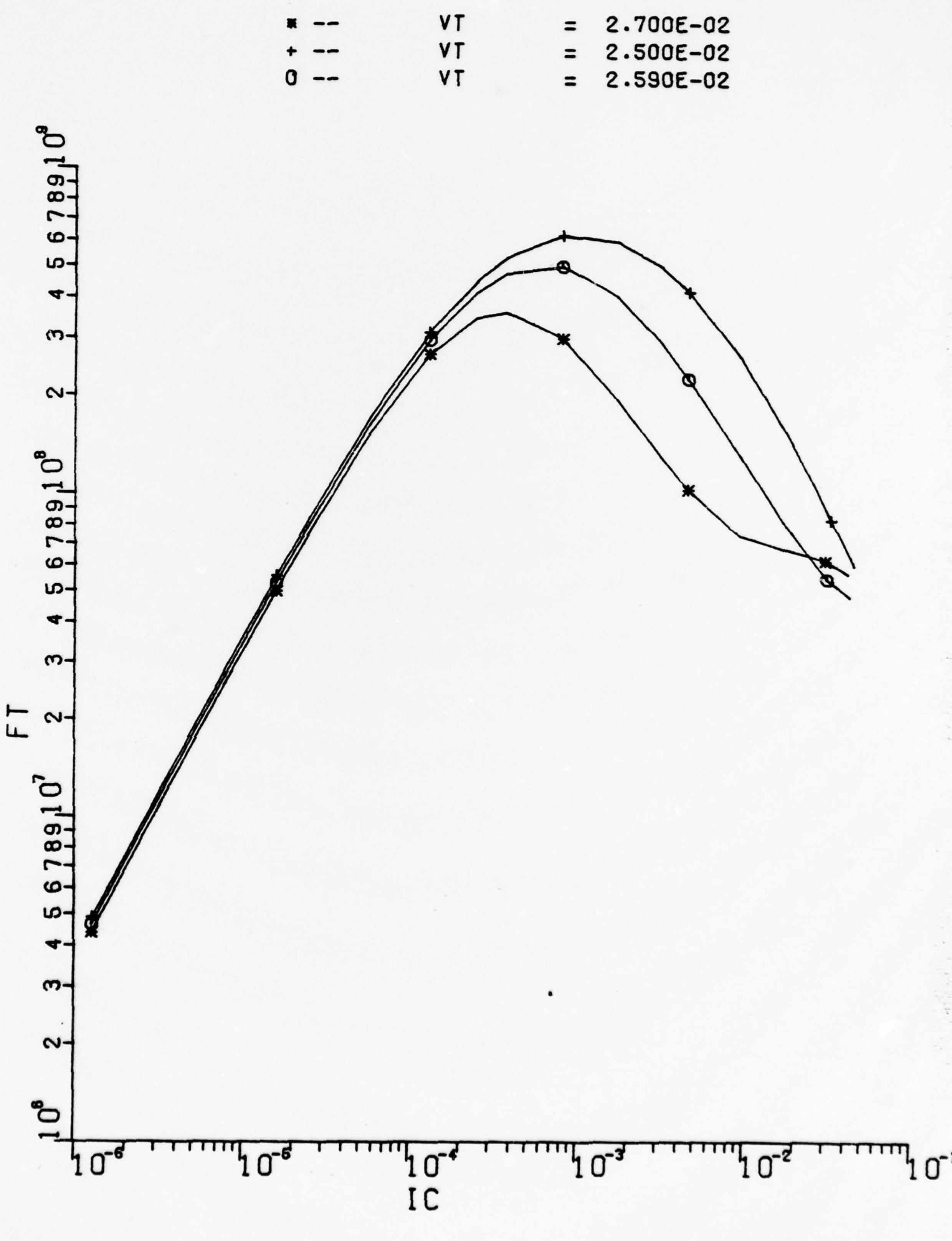
* -- IBR = 3.000E-15
+ -- IBR = 3.000E-11
0 -- IBR = 3.000E-13
FT
IC



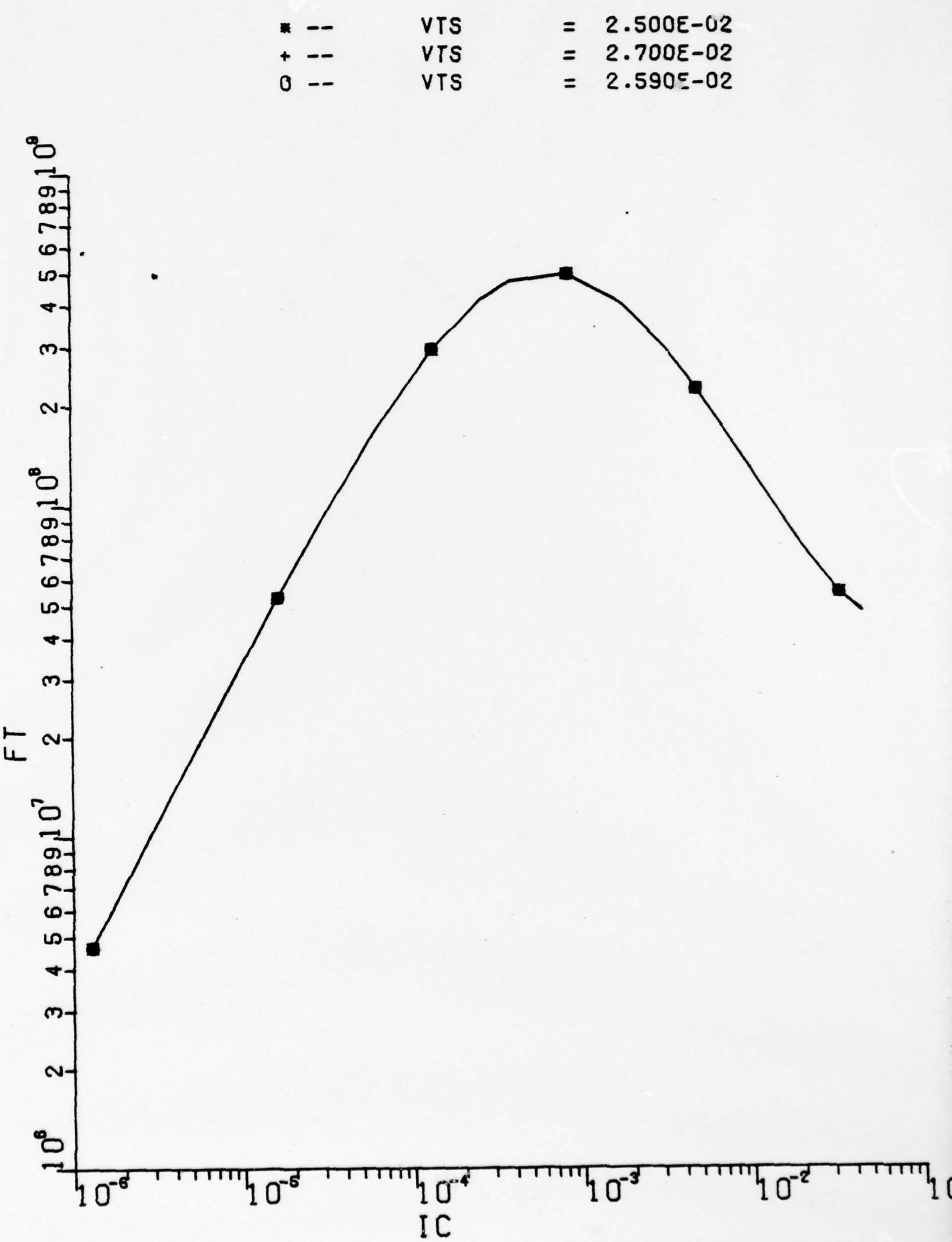
* -- VER = 5.000E+00
+ -- VER = 5.000E+01
0 -- VER = 2.000E+01
FT
IC


* -- VCR = 5.000E+00
+ -- VCR = 3.000E+02
0 -- VCR = 6.000E+01
FT
IC

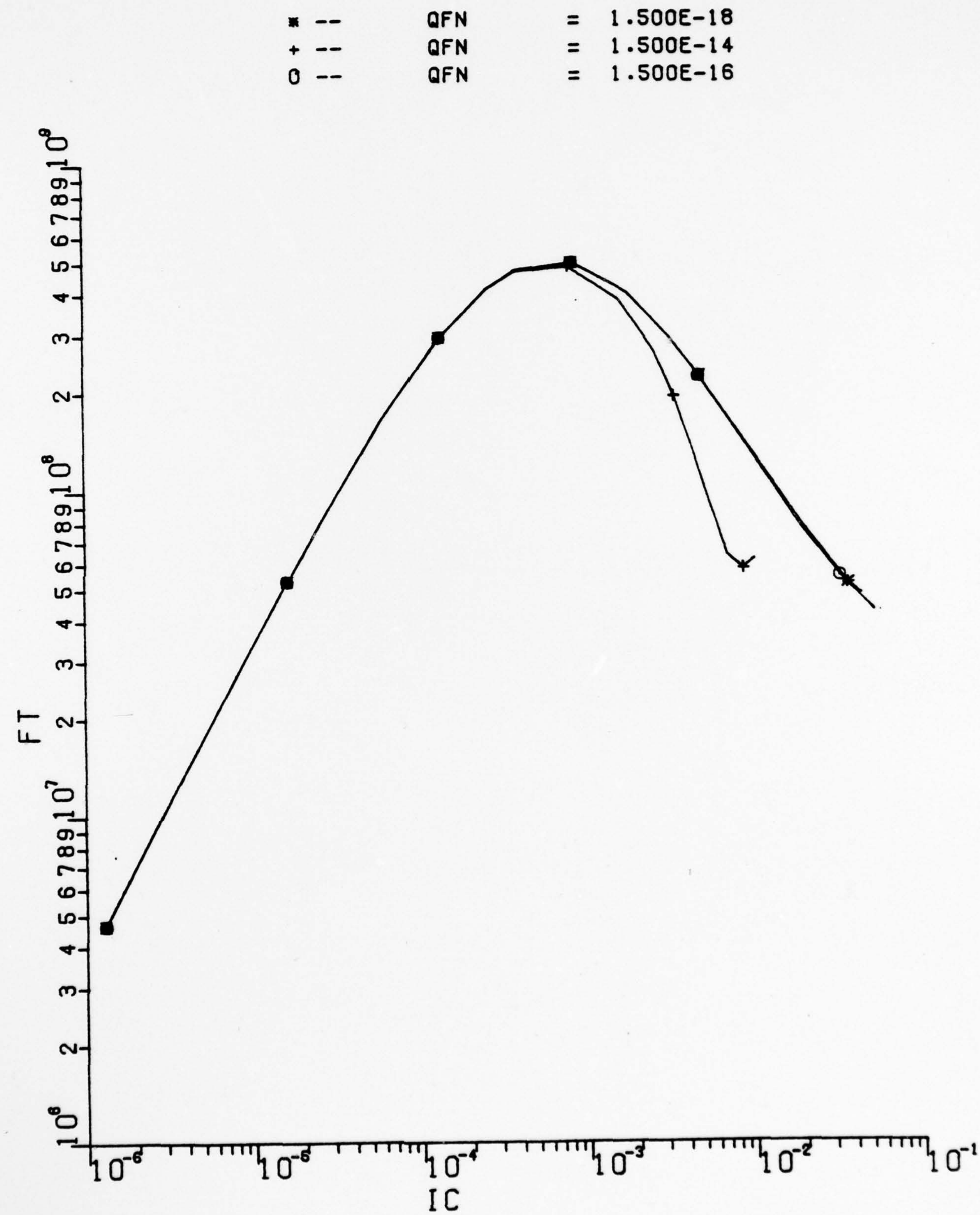

* -- NC = 8.000E-01
+ -- NC = 2.300E+00
0 -- NC = 1.800E+00
FT
IC



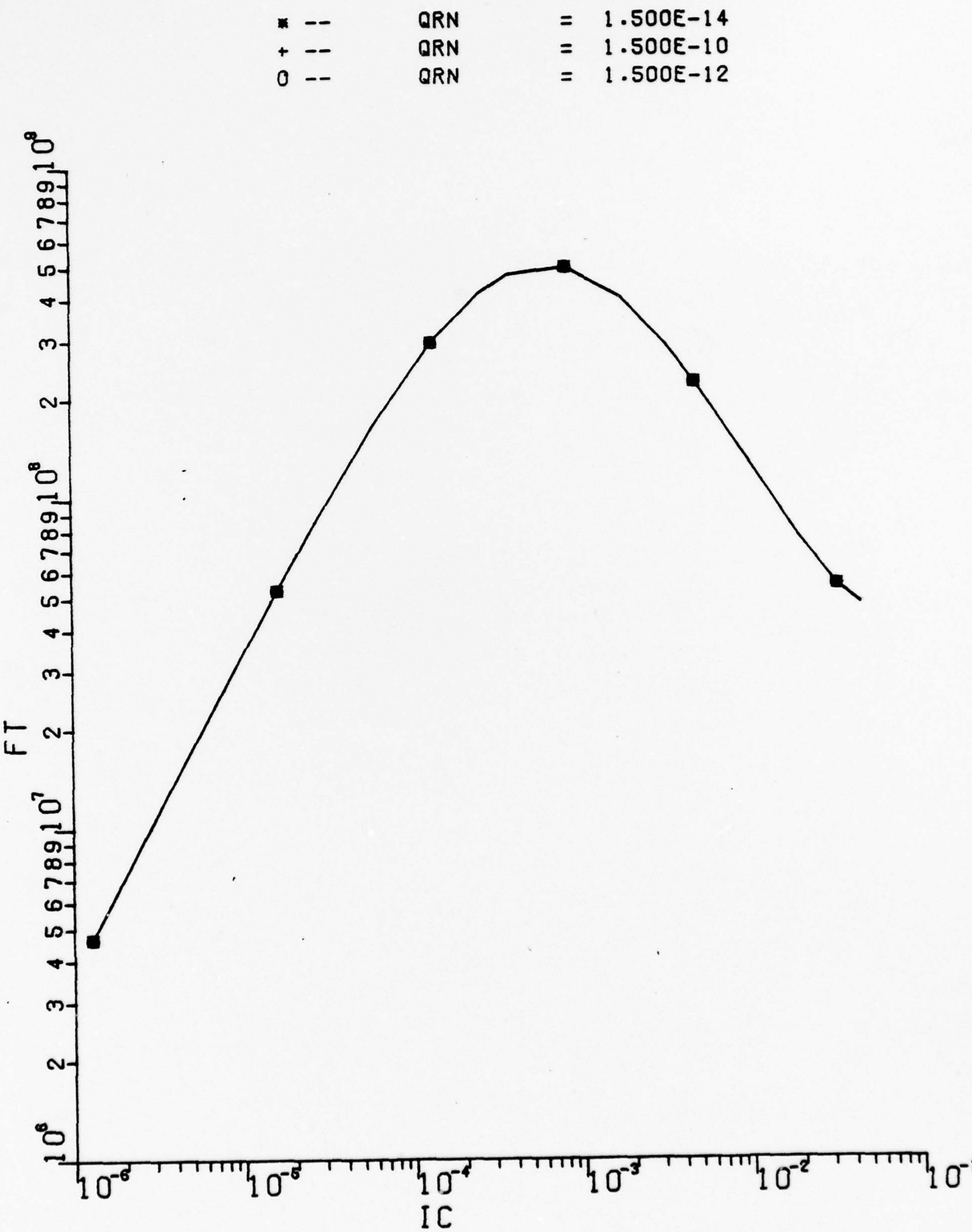
* -- VT = 2.700E-02
+ -- VT = 2.500E-02
O -- VT = 2.590E-02
FT
IC



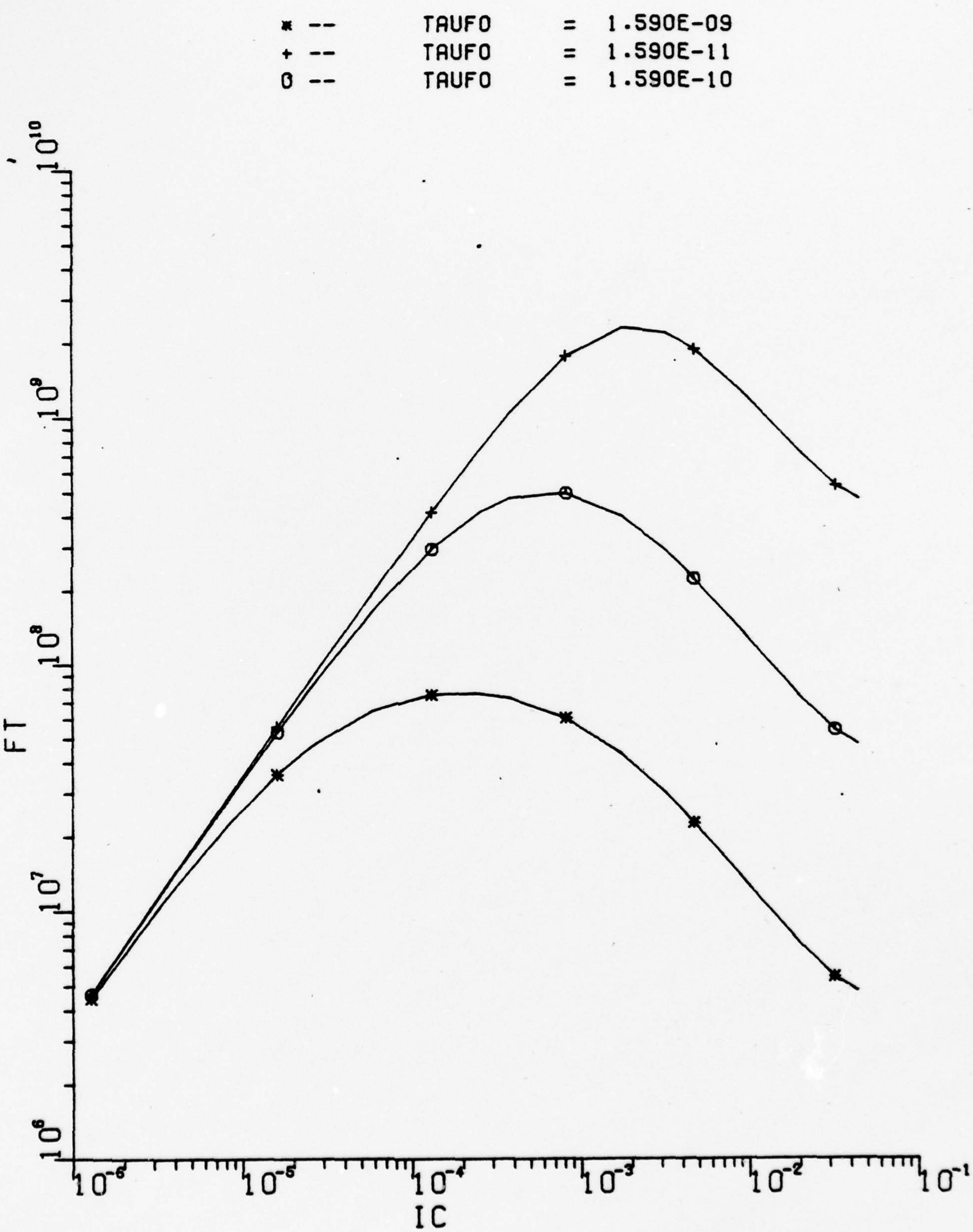
* -- VTS = 2.500E-02
+ -- VTS = 2.700E-02
0 -- VTS = 2.590E-02
FT
IC



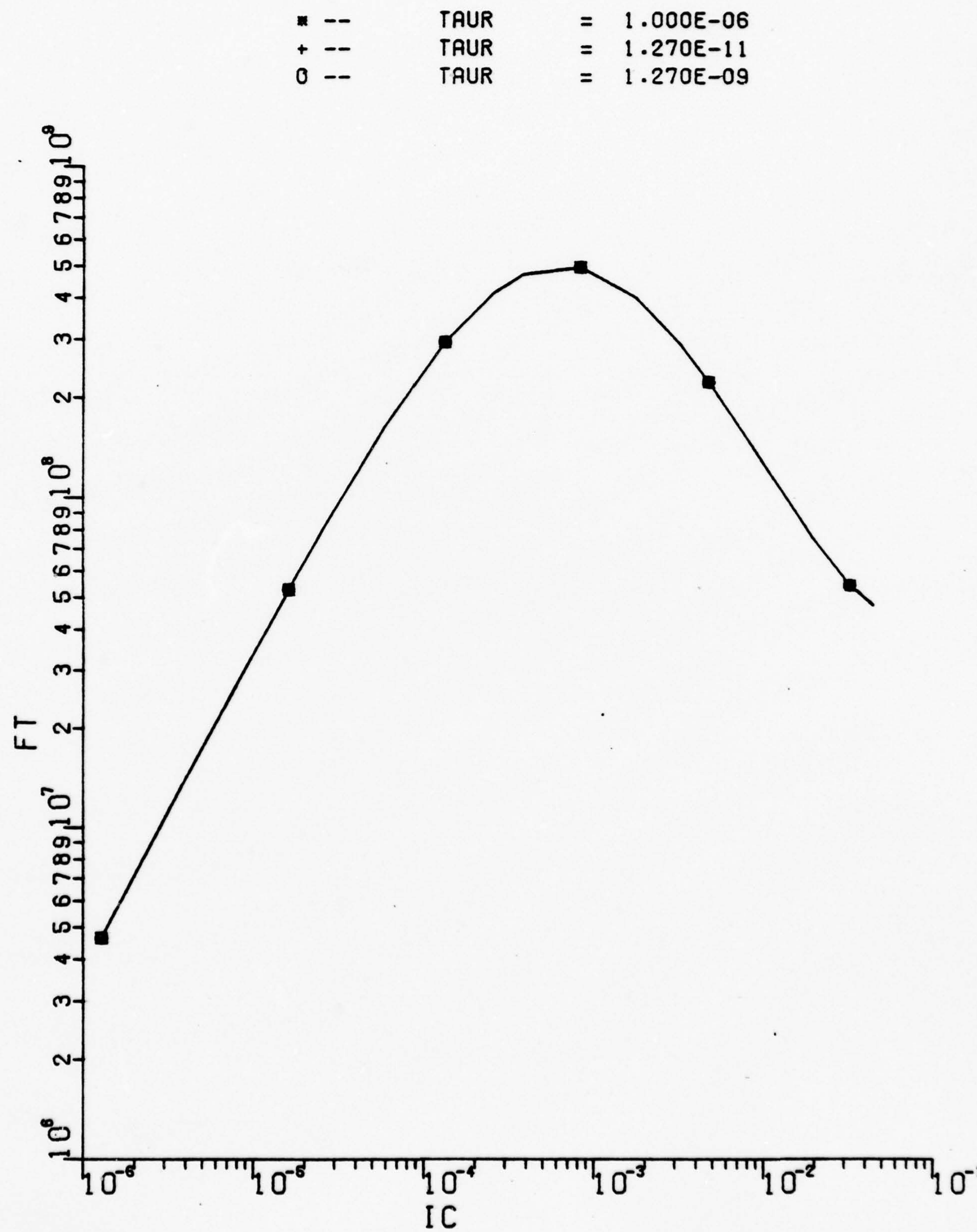
* -- QFN = 1.500E-18
+ -- QFN = 1.500E-14
O -- QFN = 1.500E-16
FT
IC
$10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$
$10^{6}$ $10^{7}$ $10^{8}$ $10^{9}$



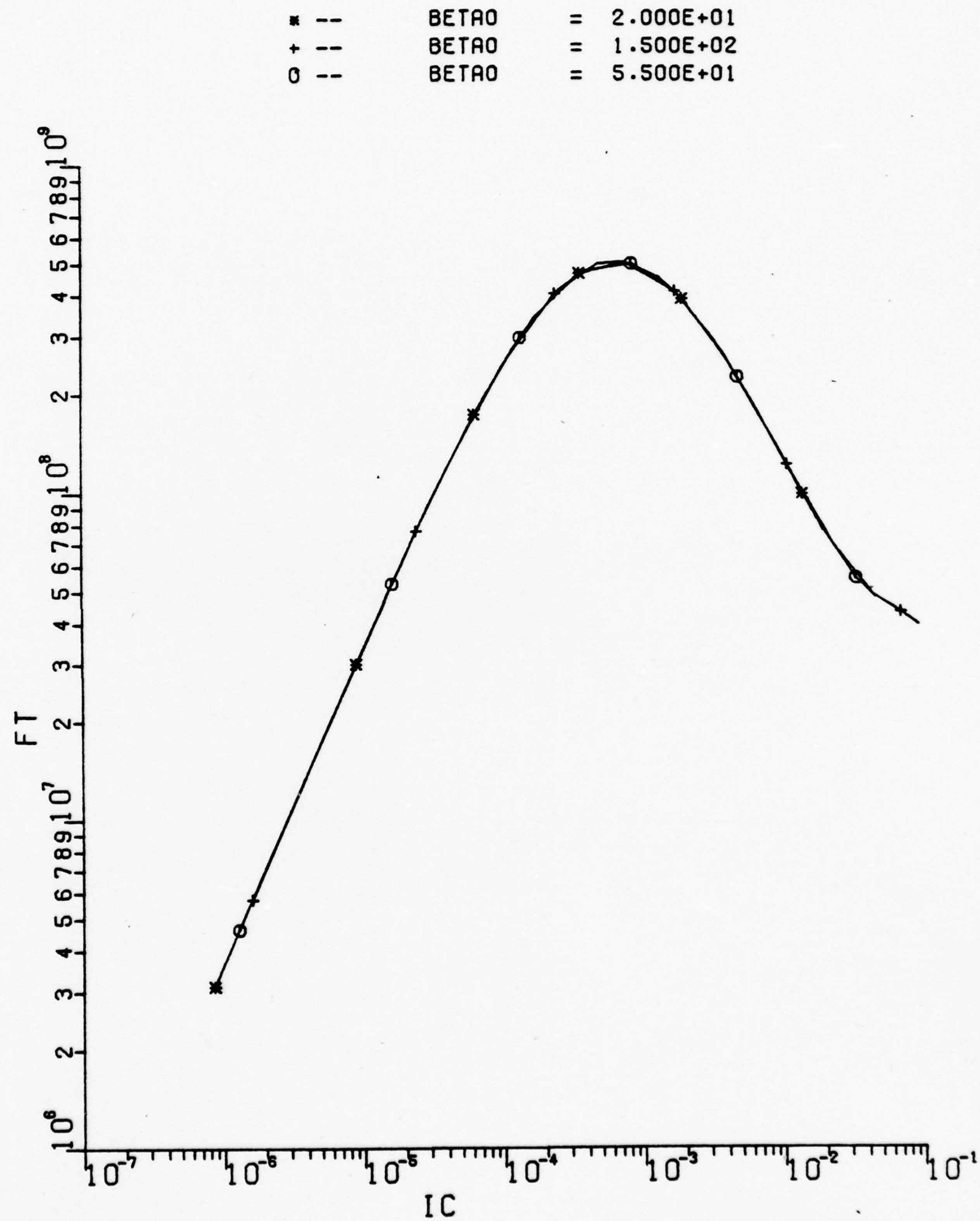
* -- QRN = 1.500E-14
+ -- QRN = 1.500E-10
0 -- QRN = 1.500E-12
FT
IC



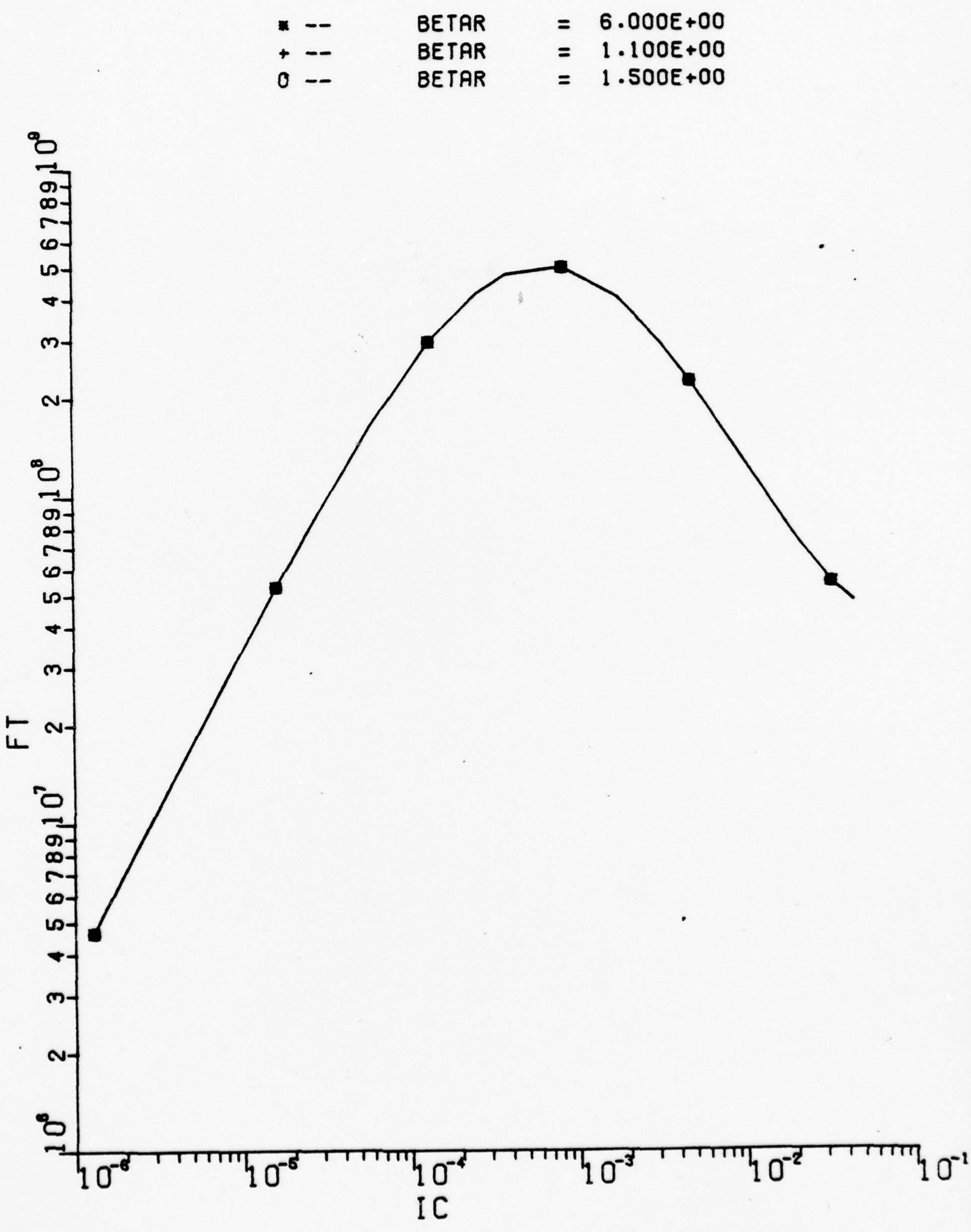
* -- TAUFO = 1.590E-09
+ -- TAUFO = 1.590E-11
O -- TAUFO = 1.590E-10
FT
IC
$10^{6}$
$10^{7}$
$10^{8}$
$10^{9}$
$10^{10}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$



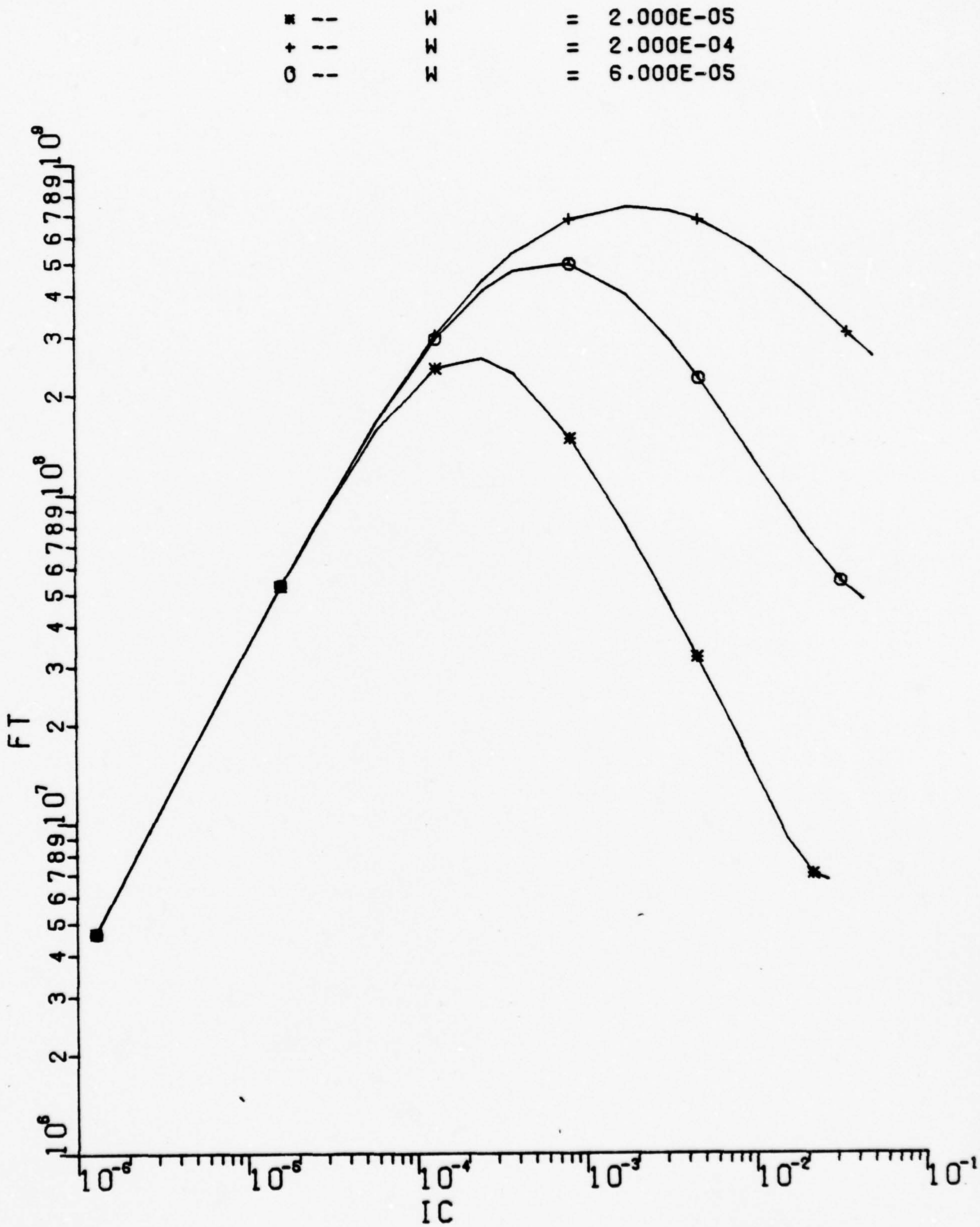
* -- TAUR = 1.000E-06
+ -- TAUR = 1.270E-11
0 -- TAUR = 1.270E-09
FT
IC



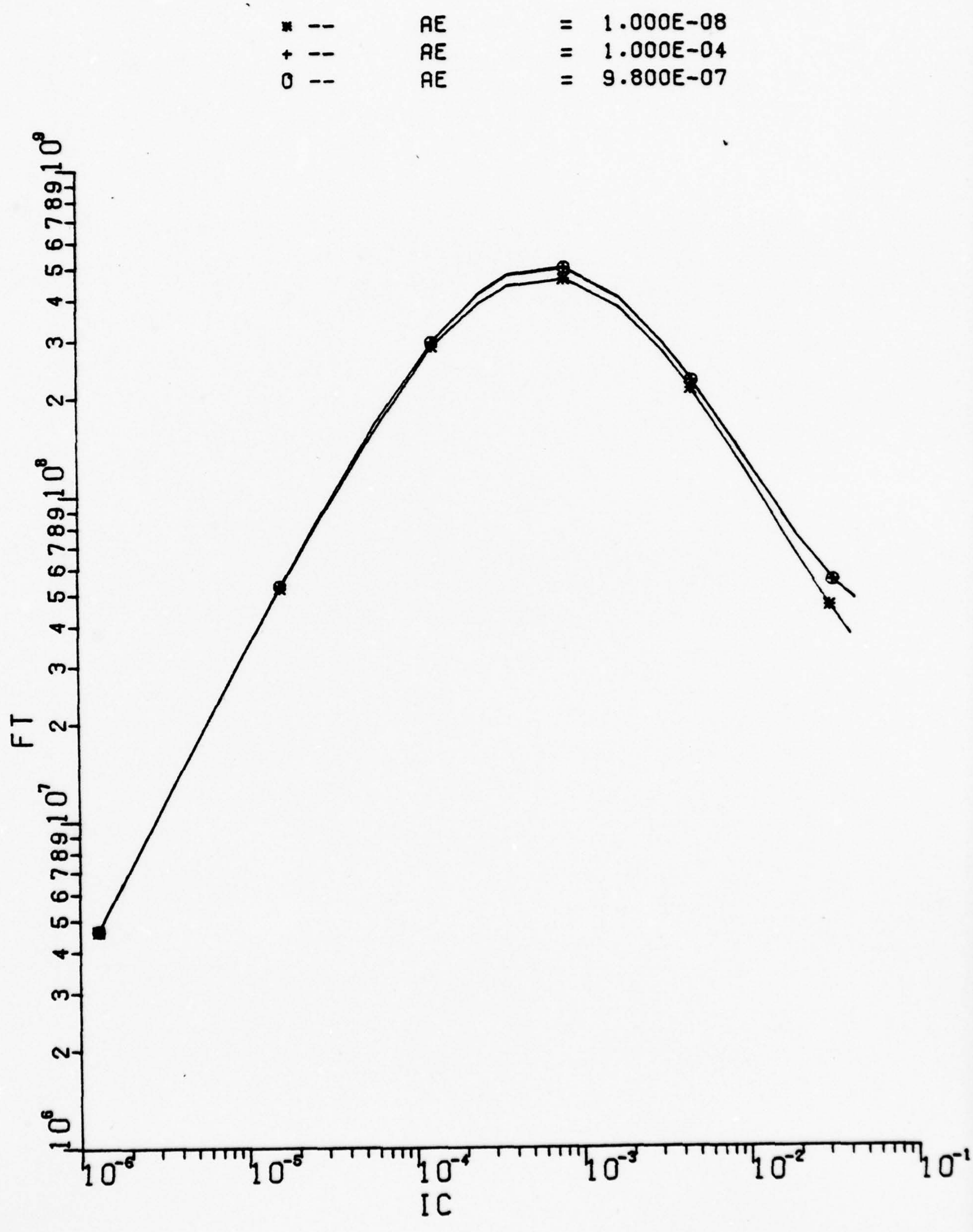
* -- BETAO = 2.000E+01
+ -- BETAO = 1.500E+02
O -- BETAO = 5.500E+01
FT
IC



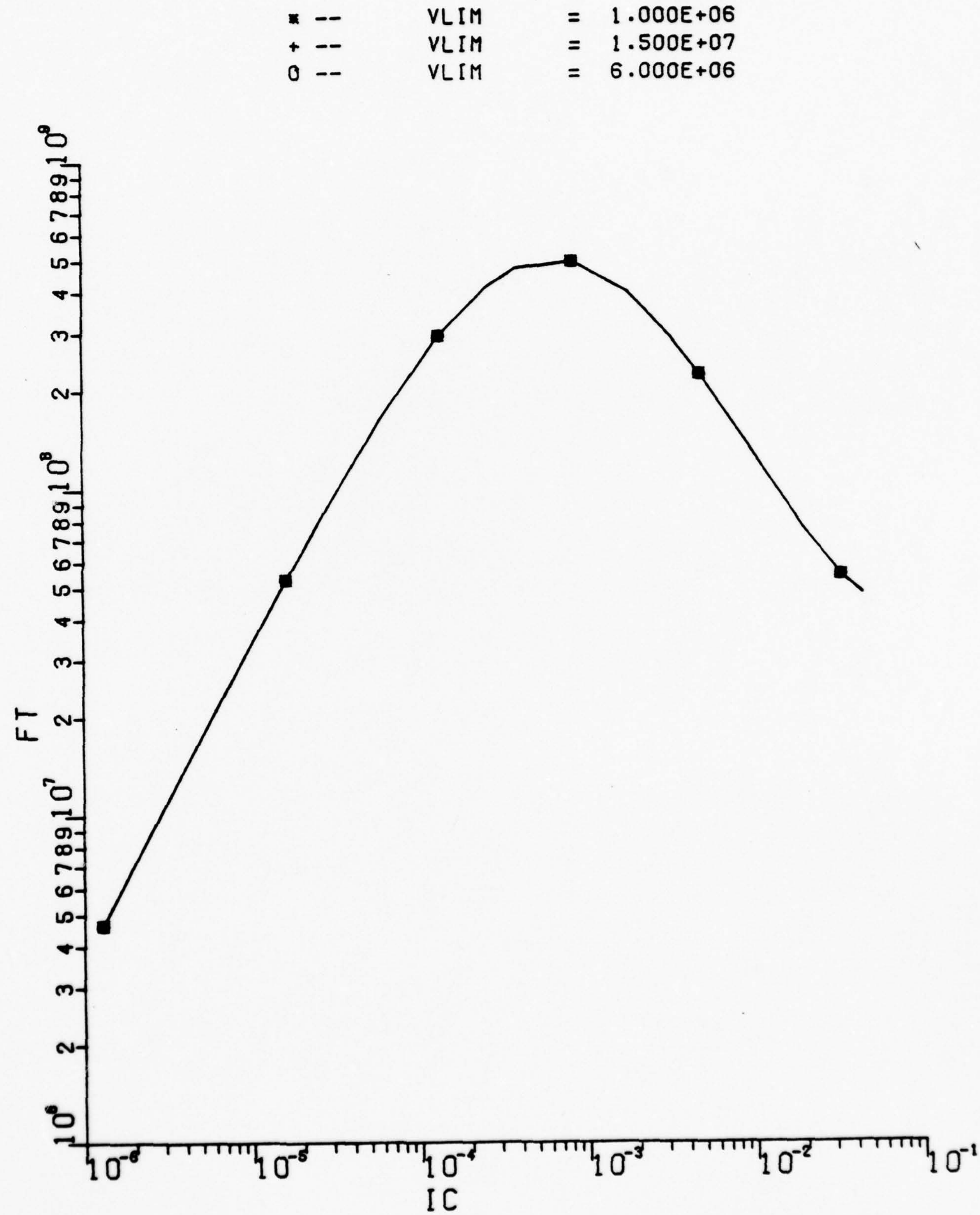
* -- BETAR = 6.000E+00
+ -- BETAR = 1.100E+00
O -- BETAR = 1.500E+00
FT
IC



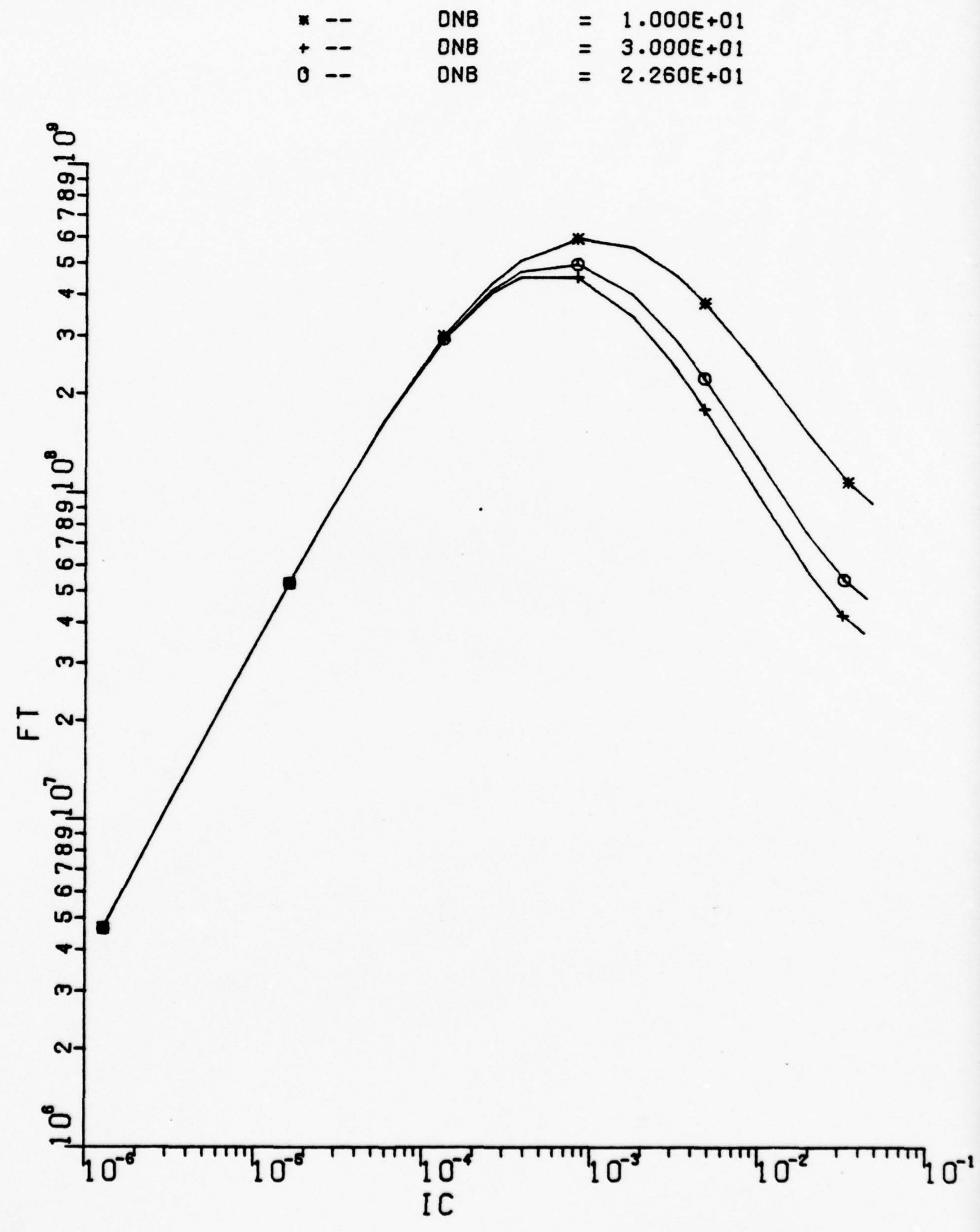
* -- W = 2.000E-05
+ -- W = 2.000E-04
O -- W = 6.000E-05
FT
IC



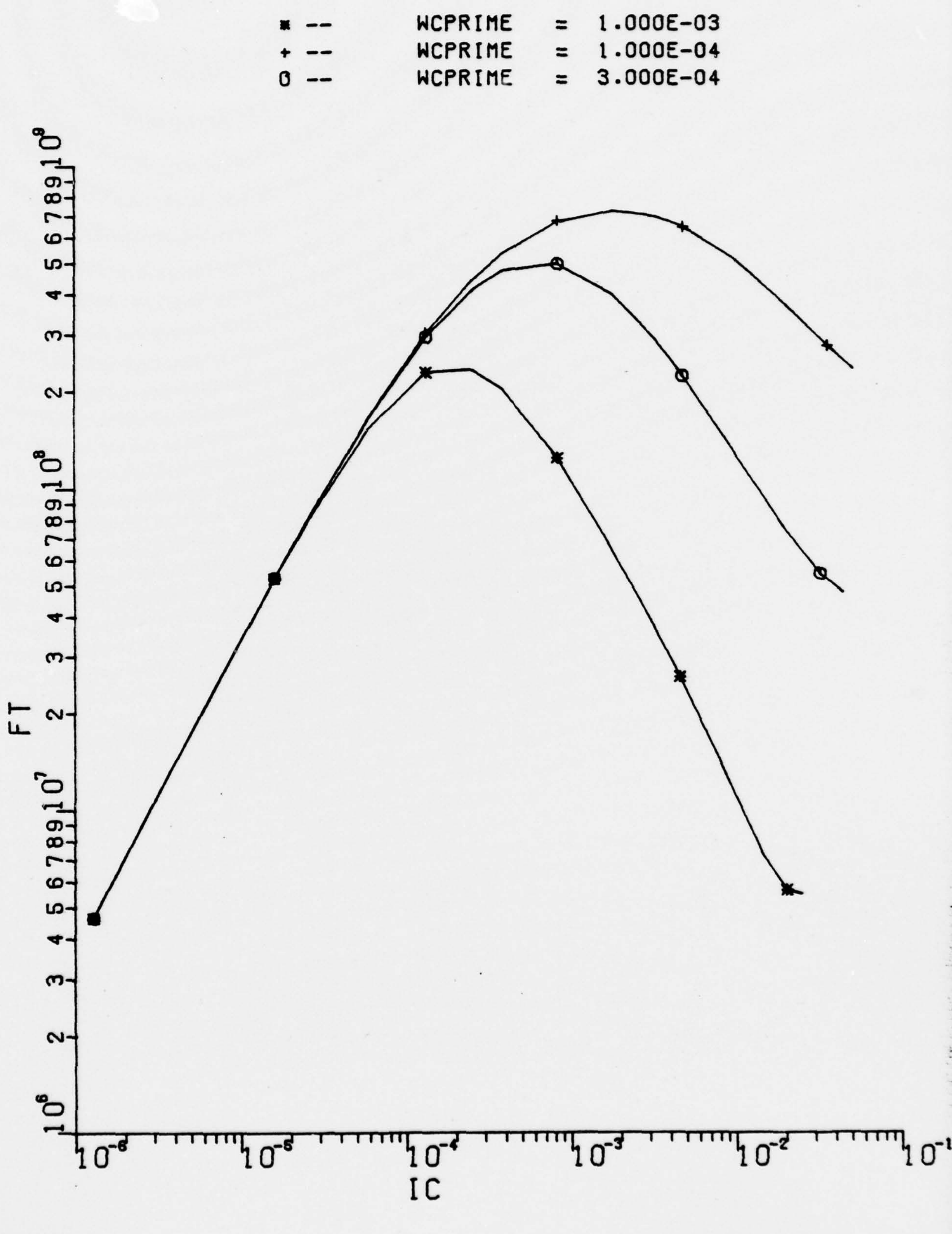
* -- AE = 1.000E-08
+ -- AE = 1.000E-04
O -- AE = 9.800E-07
FT
IC



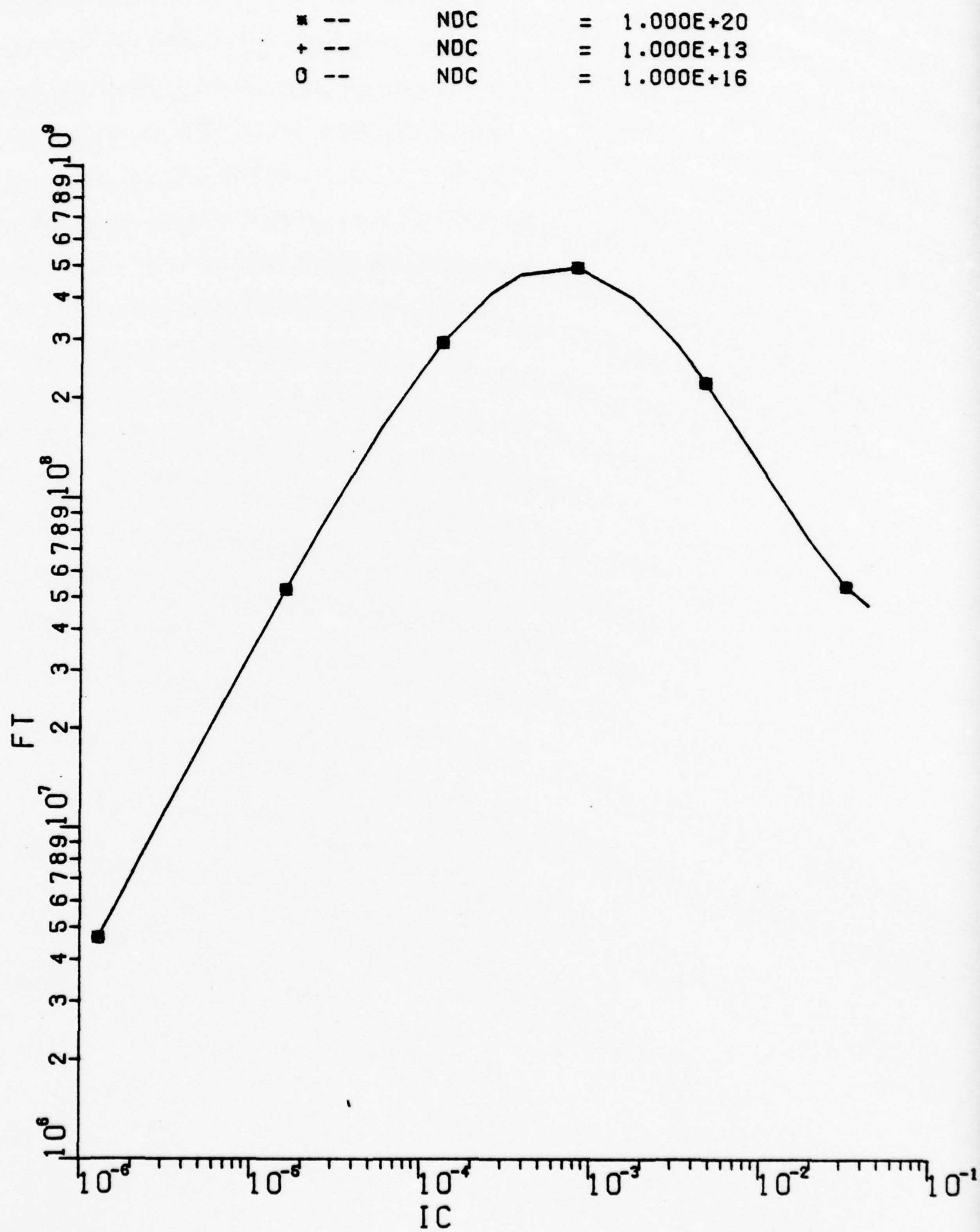
* -- VLIM = 1.000E+06
+ -- VLIM = 1.500E+07
0 -- VLIM = 6.000E+06
FT
IC

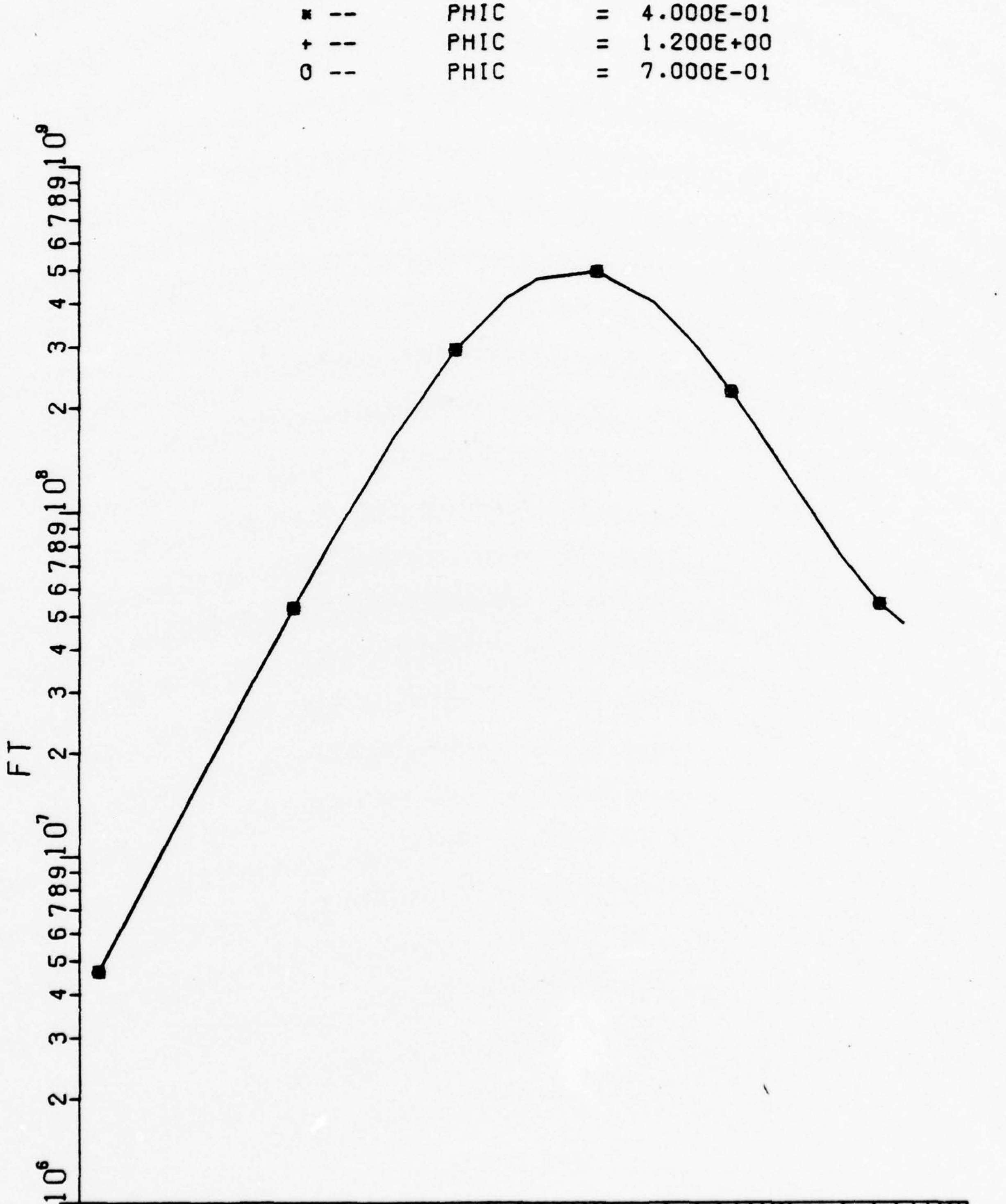


* -- DNB = 1.000E+01
+ -- DNB = 3.000E+01
O -- DNB = 2.260E+01
FT
IC

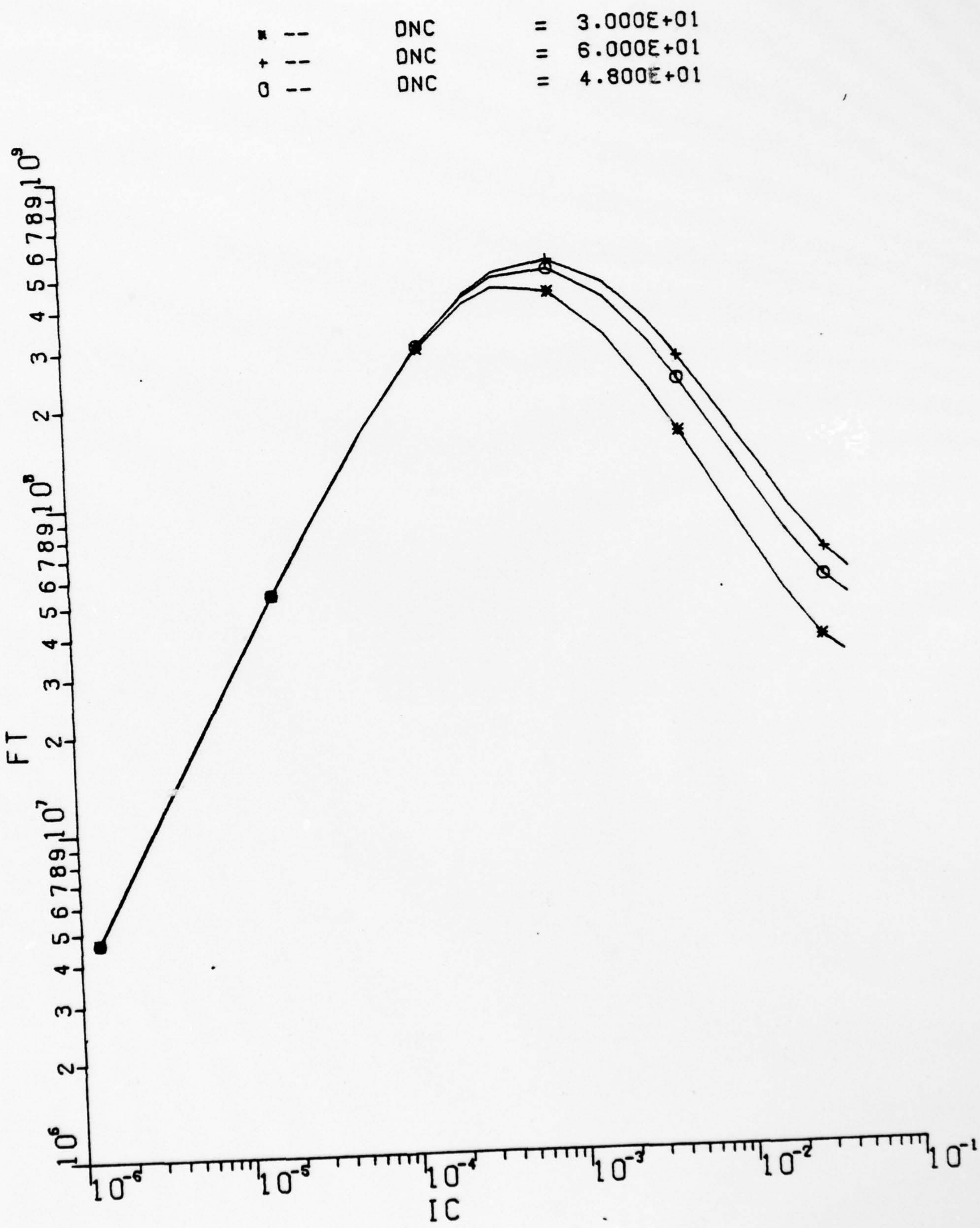


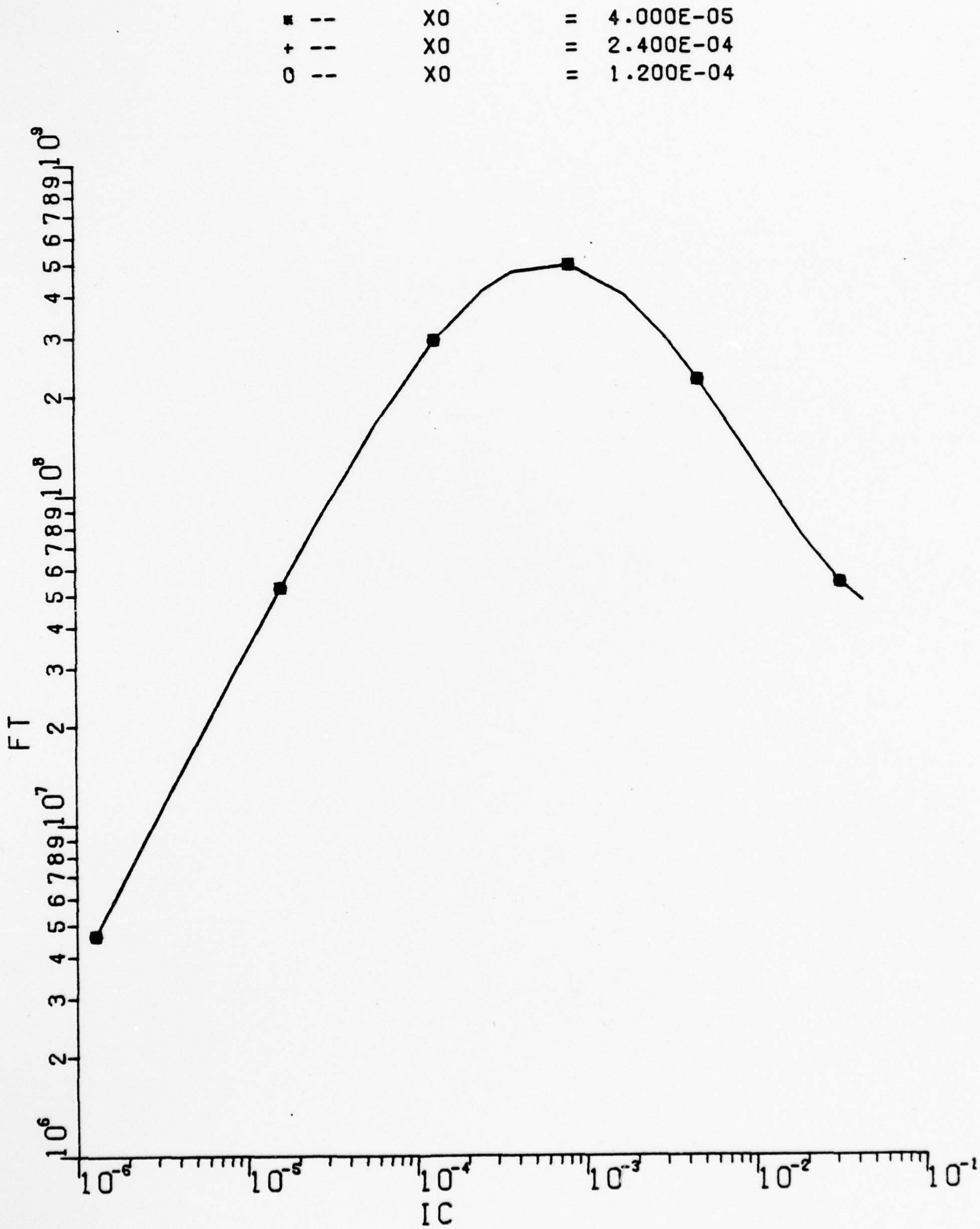
* -- WCPRIME = 1.000E-03
+ -- WCPRIME = 1.000E-04
0 -- WCPRIME = 3.000E-04
FT
IC


* -- NDC = 1.000E+20
+ -- NDC = 1.000E+13
0 -- NDC = 1.000E+16
FT
IC
$10^{6}$
$10^{7}$
$10^{8}$
$10^{9}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$

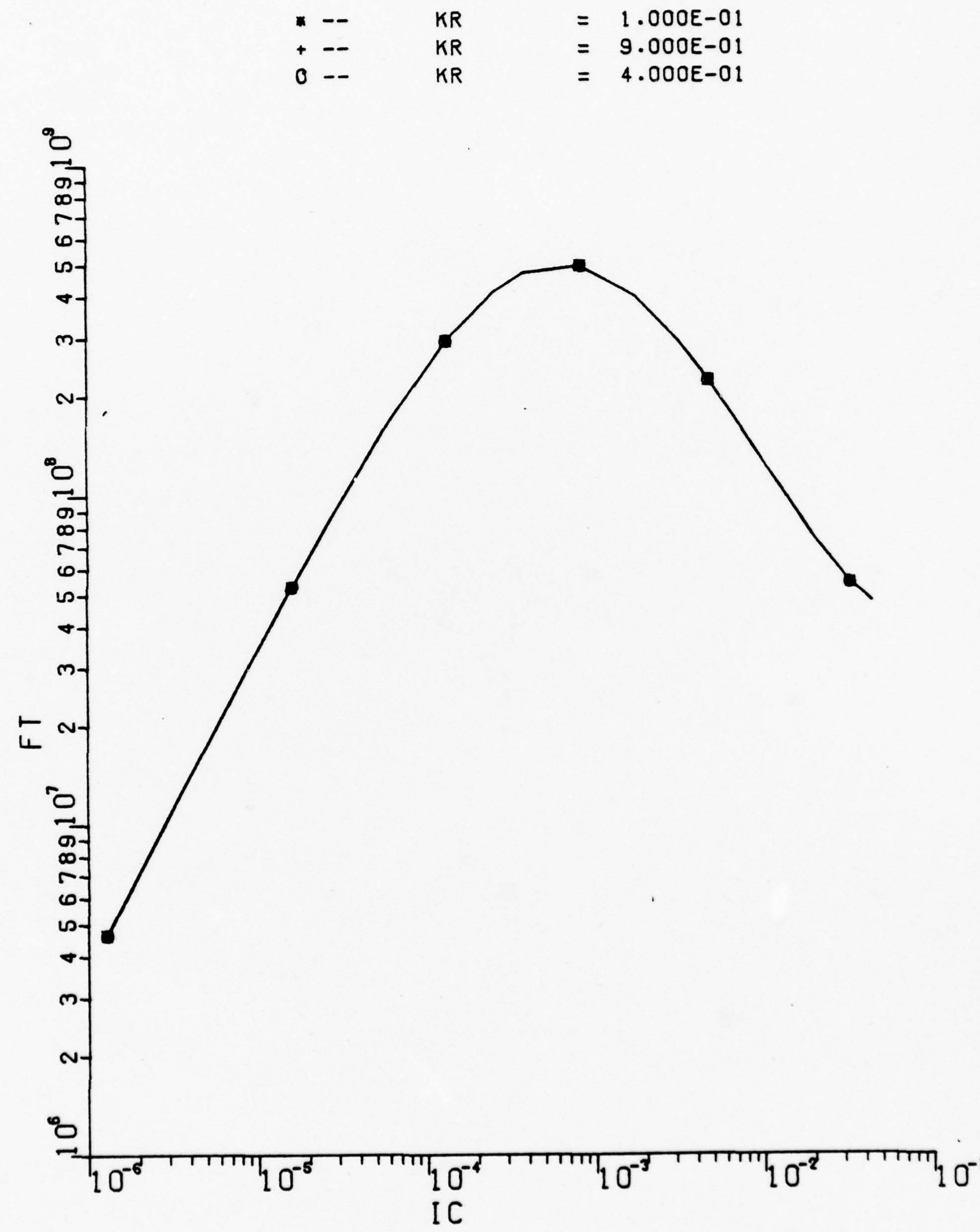


* -- PHIC = 4.000E-01
+ -- PHIC = 1.200E+00
O -- PHIC = 7.000E-01
FT
IC

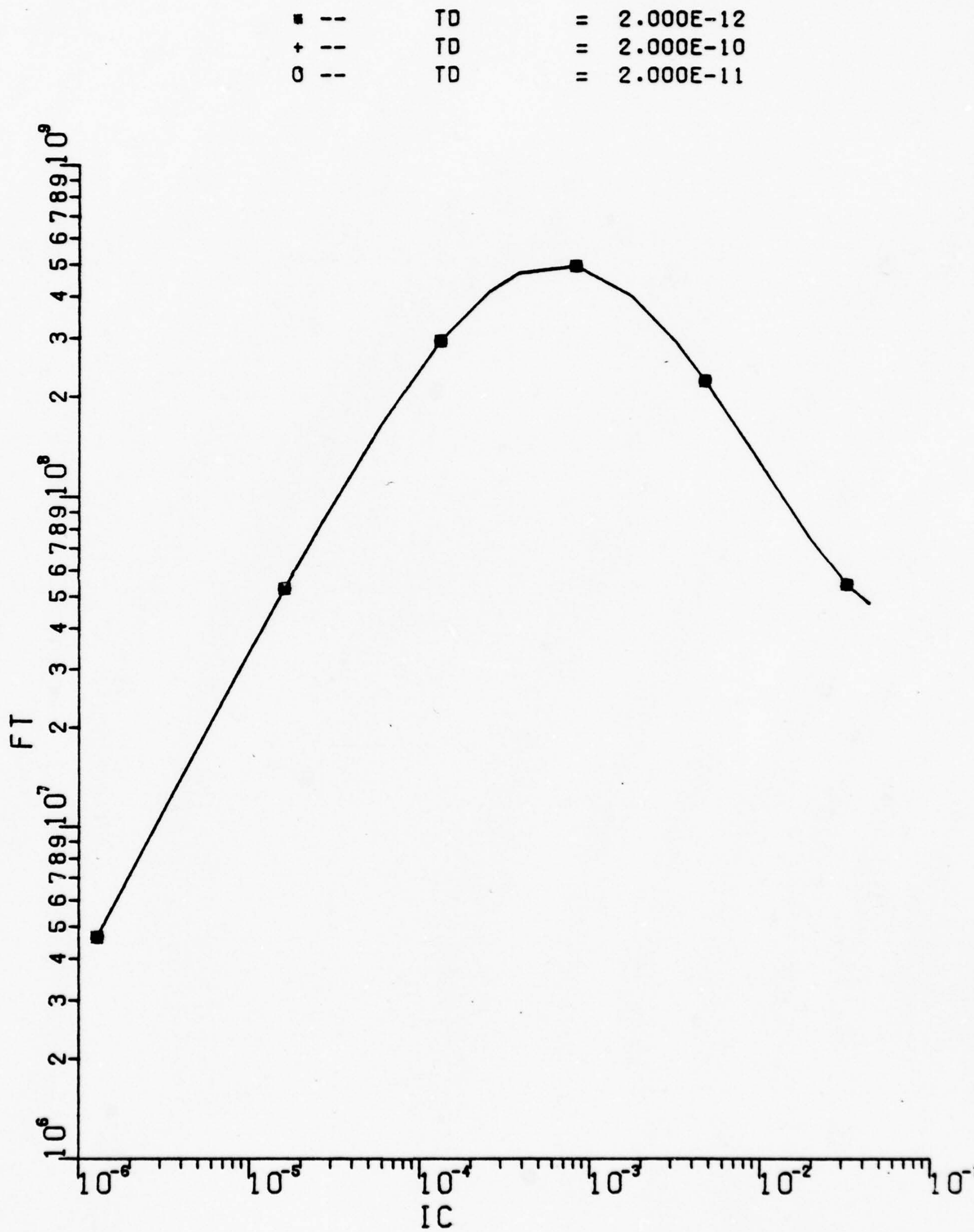

* -- DNC = 3.000E+01
+ -- DNC = 6.000E+01
O -- DNC = 4.800E+01
FT
IC

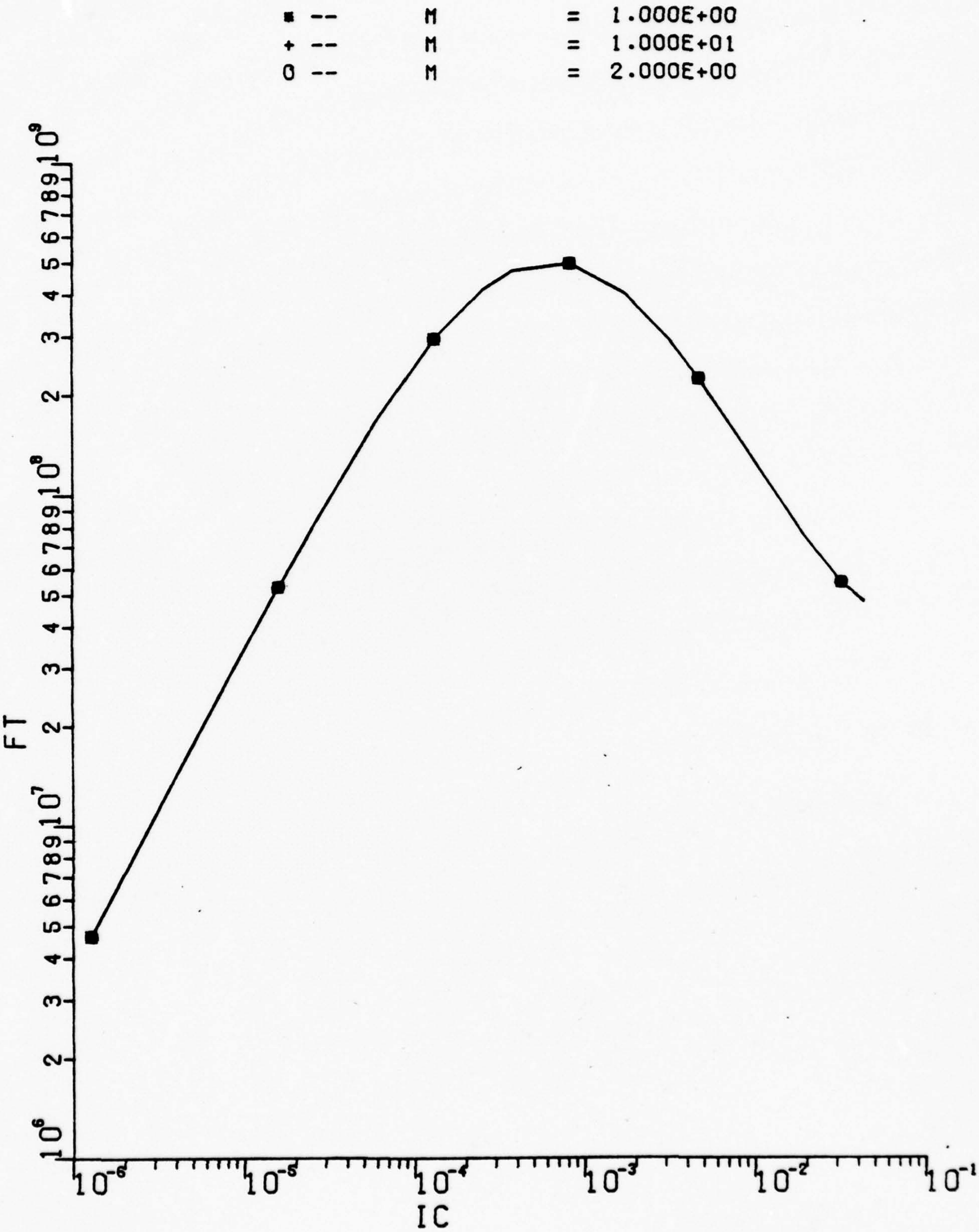


* -- XO = 4.000E-05
+ -- XO = 2.400E-04
0 -- XO = 1.200E-04
FT
IC

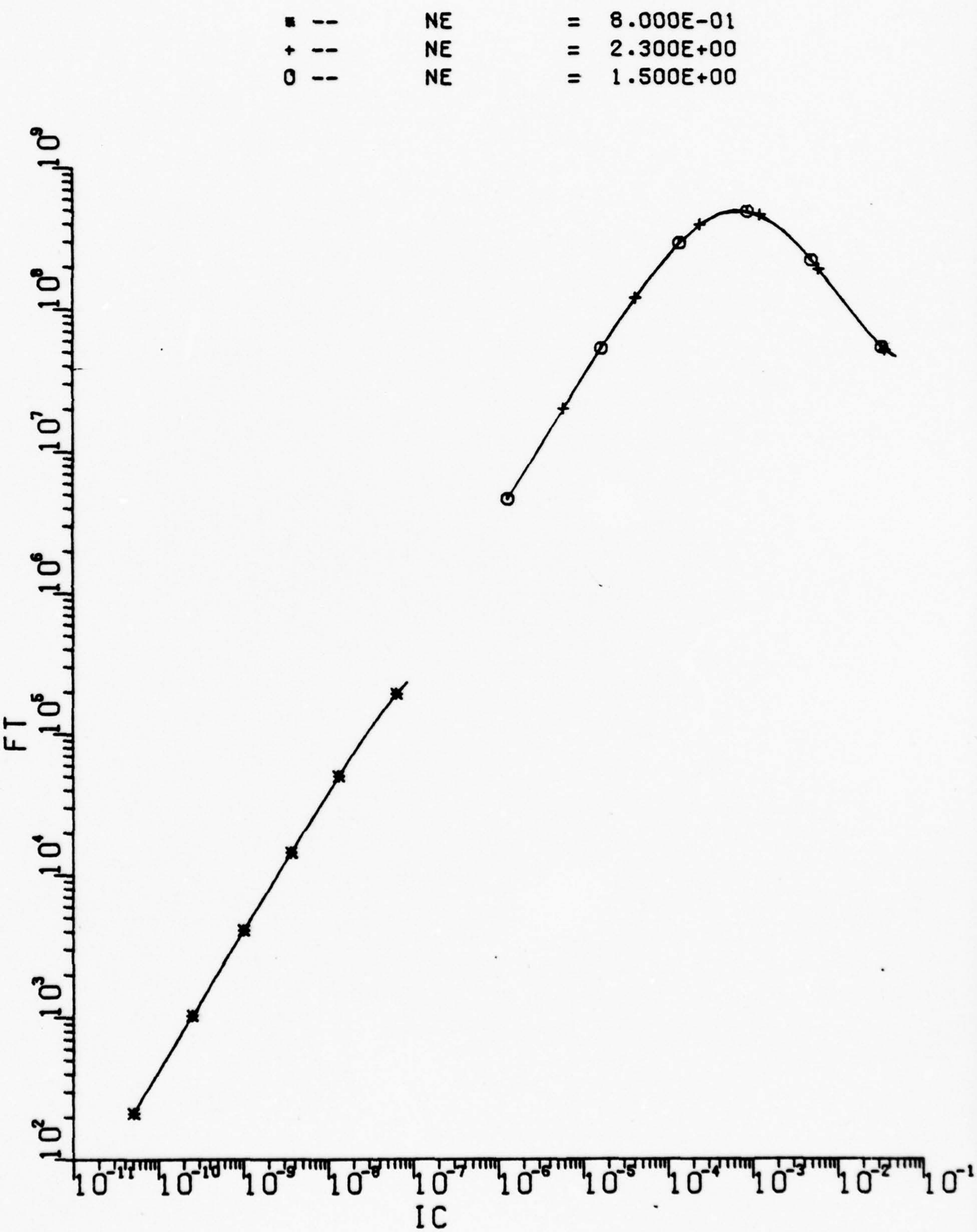


* -- KR = 1.000E-01
+ -- KR = 9.000E-01
0 -- KR = 4.000E-01
FT
IC

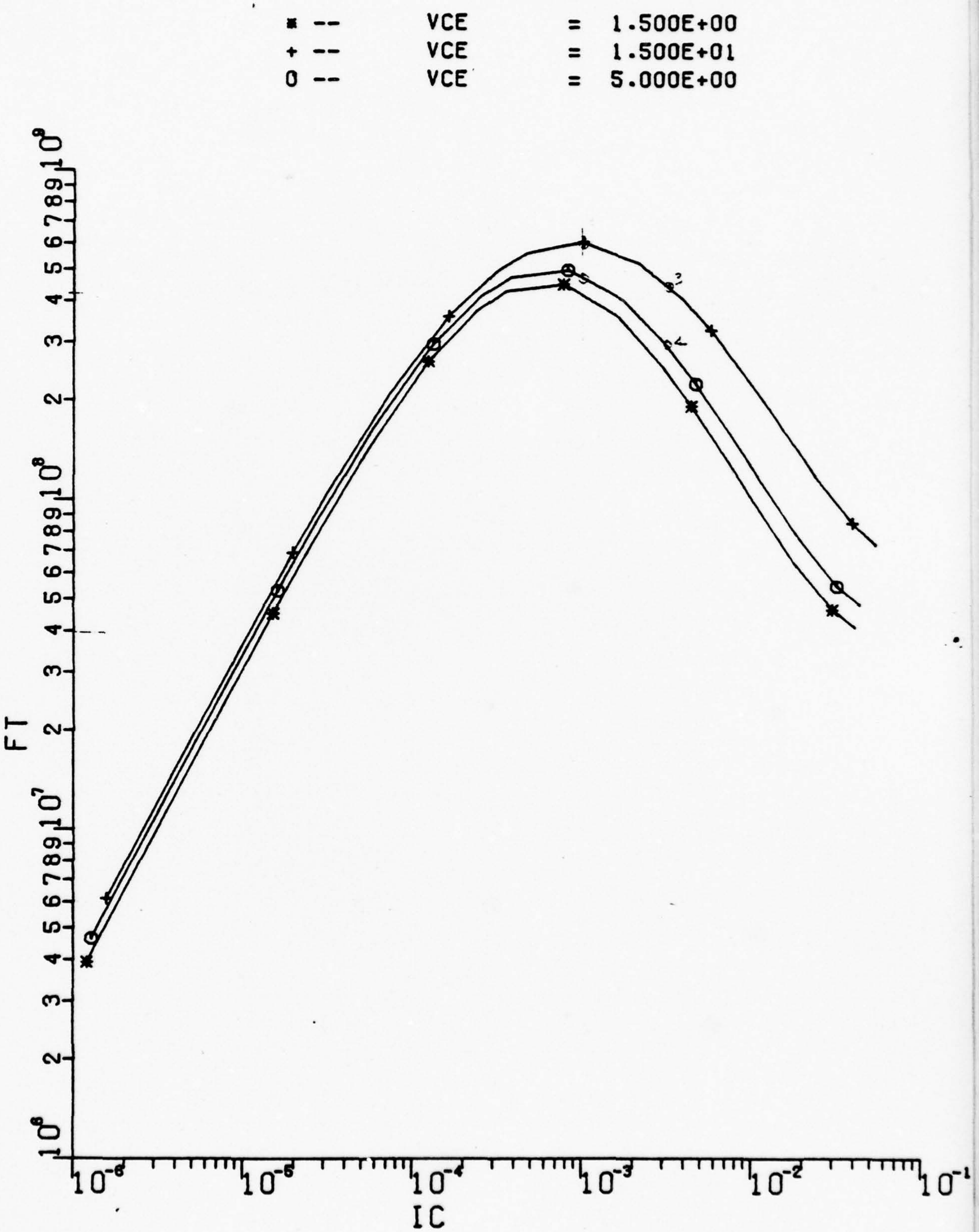

* -- TD = 2.000E-12
+ -- TD = 2.000E-10
0 -- TD = 2.000E-11
FT
IC
$10^{6}$
$10^{7}$
$10^{8}$
$10^{9}$
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$



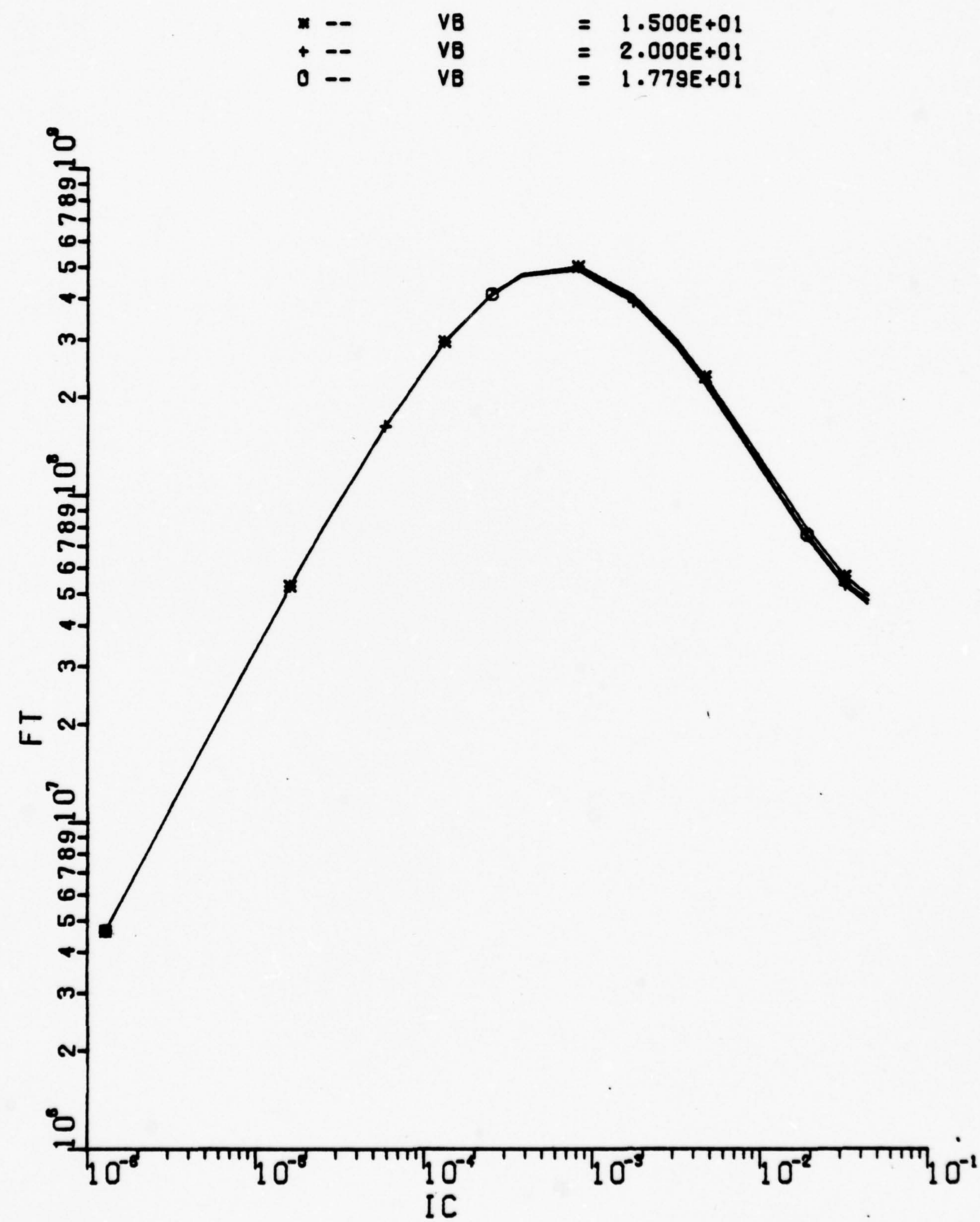
■ -- M = 1.000E+00
+ -- M = 1.000E+01
O -- M = 2.000E+00
FT
IC



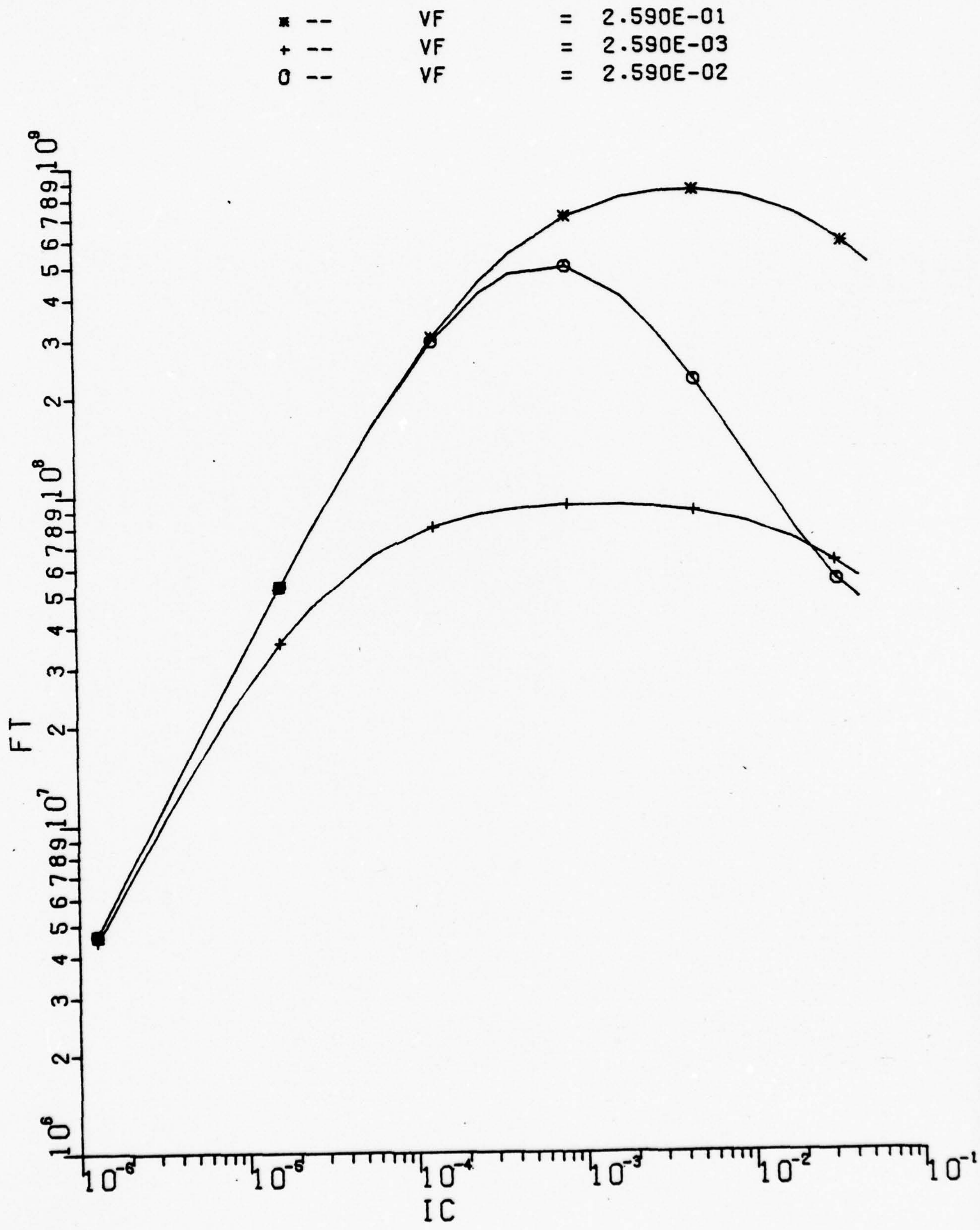
* -- NE = 8.000E-01
+ -- NE = 2.300E+00
O -- NE = 1.500E+00
FT
IC



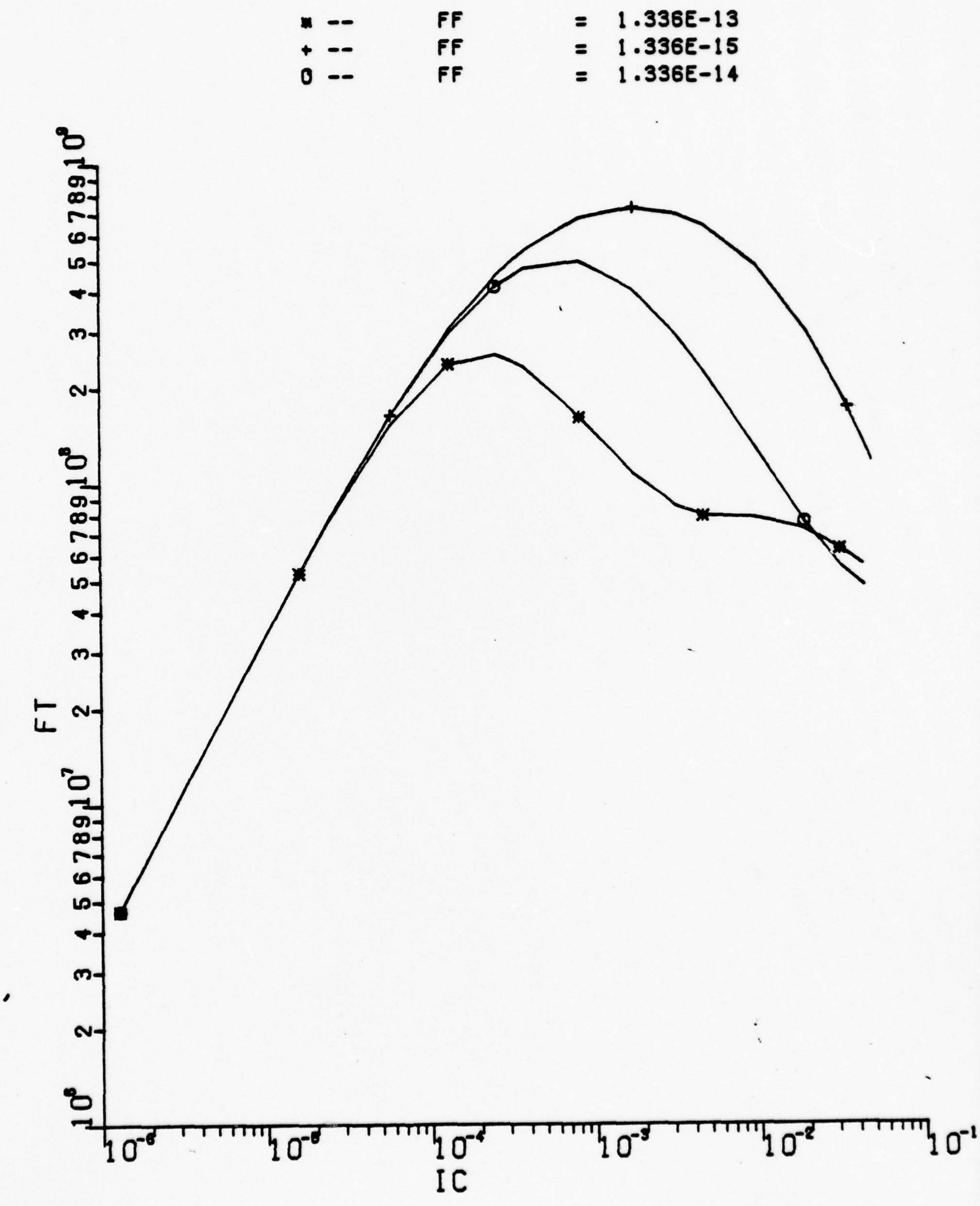
* -- VCE = 1.500E+00
+ -- VCE = 1.500E+01
0 -- VCE = 5.000E+00
FT
IC



* -- VB = 1.500E+01
+ -- VB = 2.000E+01
0 -- VB = 1.779E+01
FT
IC



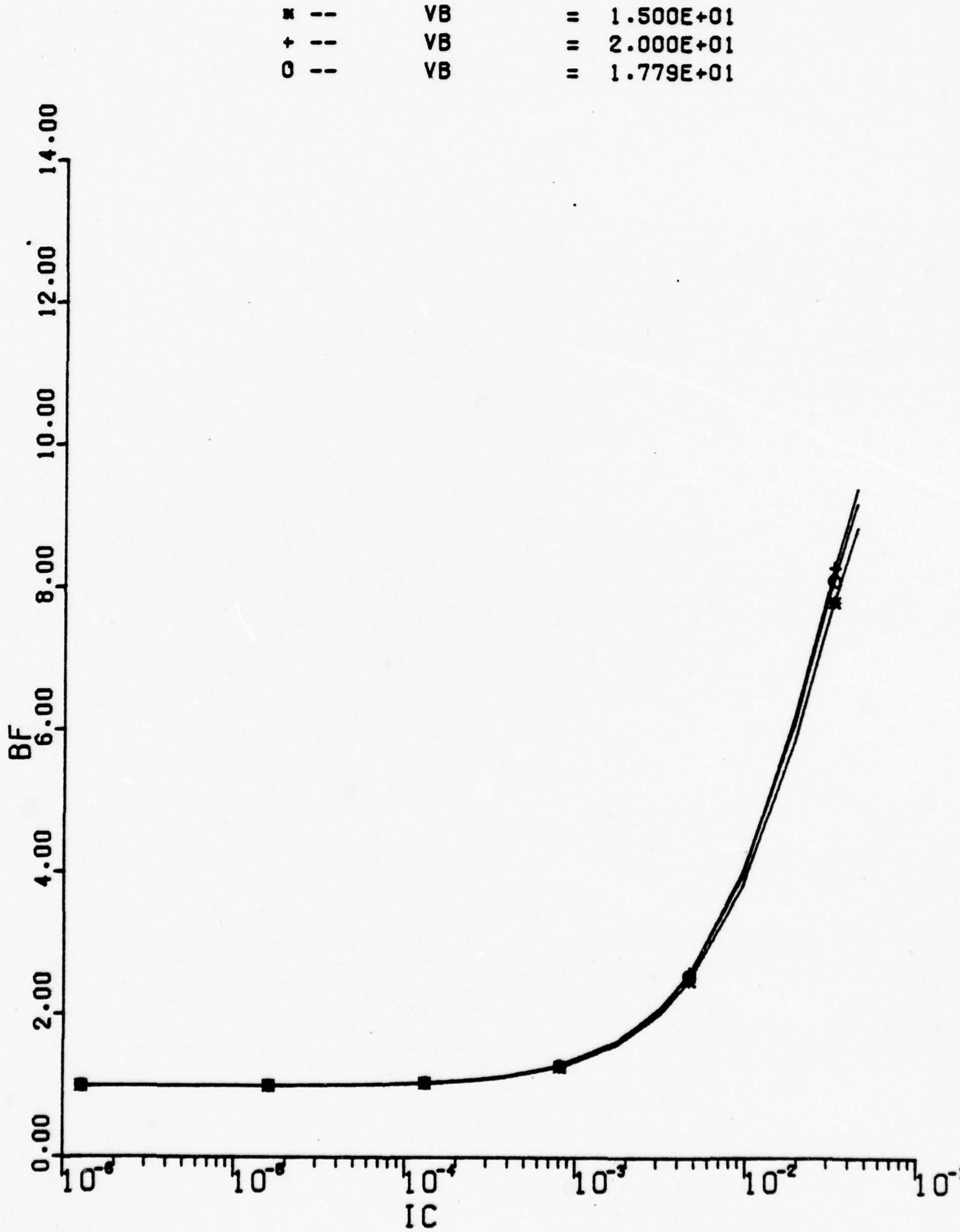
* -- VF = 2.590E-01
+ -- VF = 2.590E-03
O -- VF = 2.590E-02
FT
IC



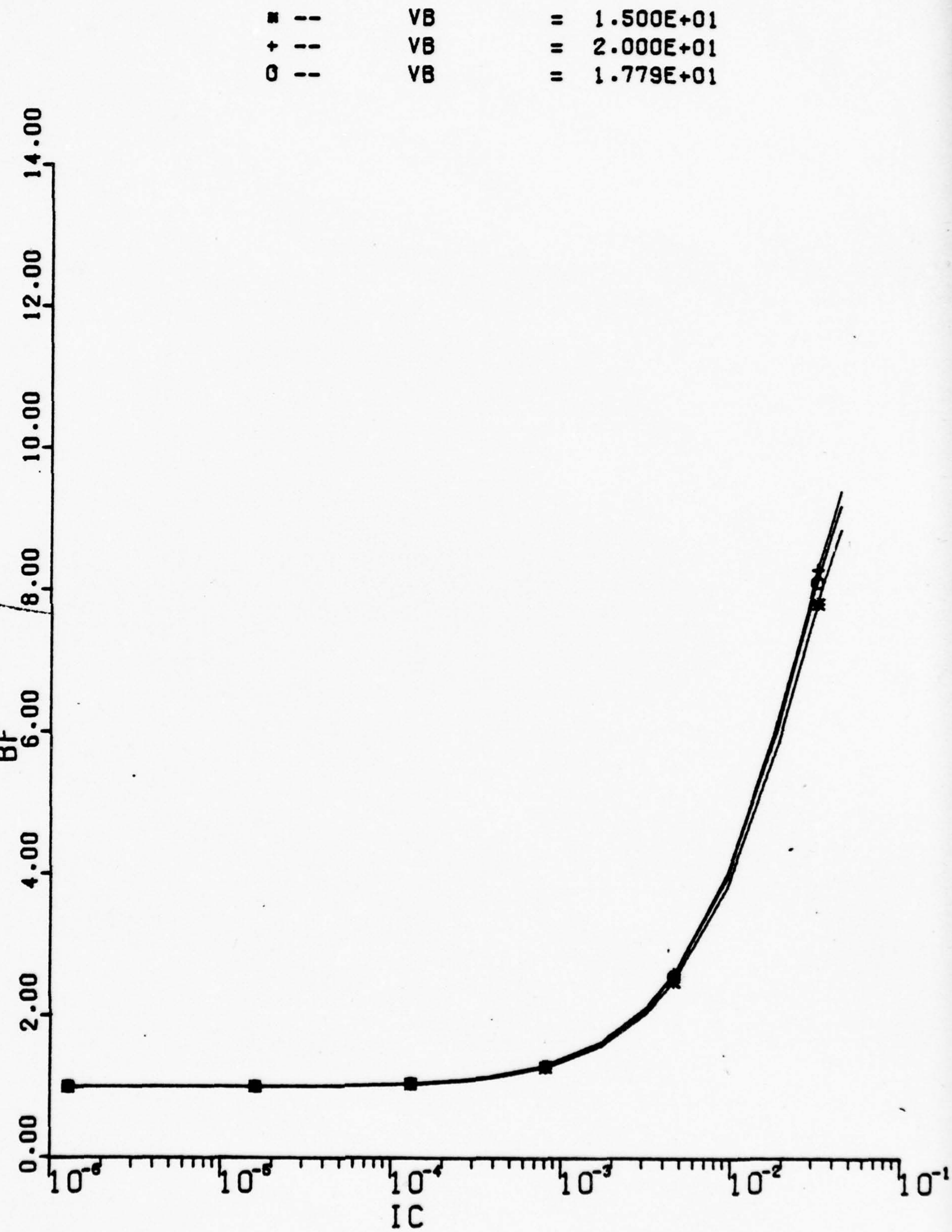
* -- FF = 1.336E-13
+ -- FF = 1.336E-15
O -- FF = 1.336E-14
FT
IC

## B.5 $B_F$ vs. $I_c$ Curves

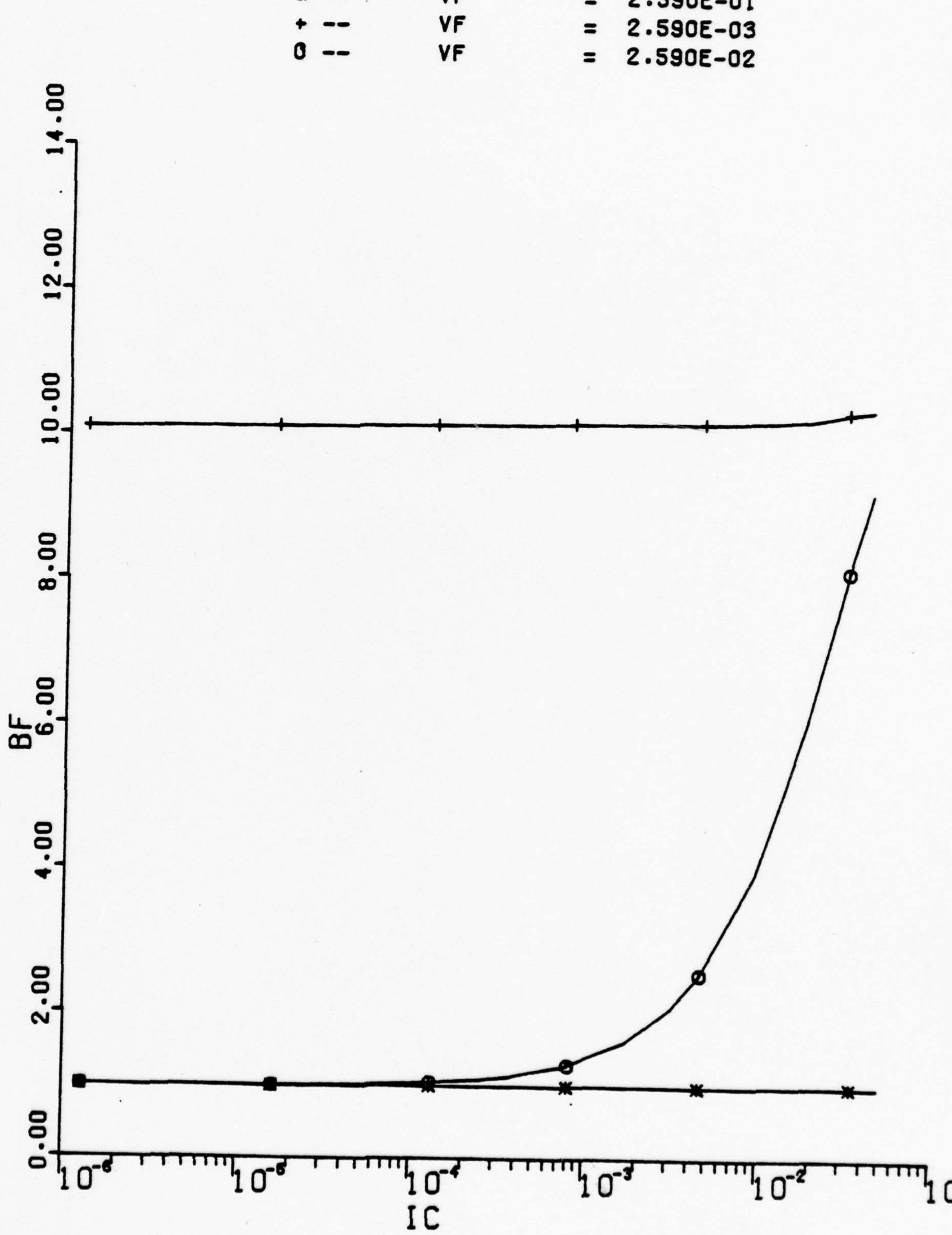
## (BASE PUSHOUT PARAMETERS)

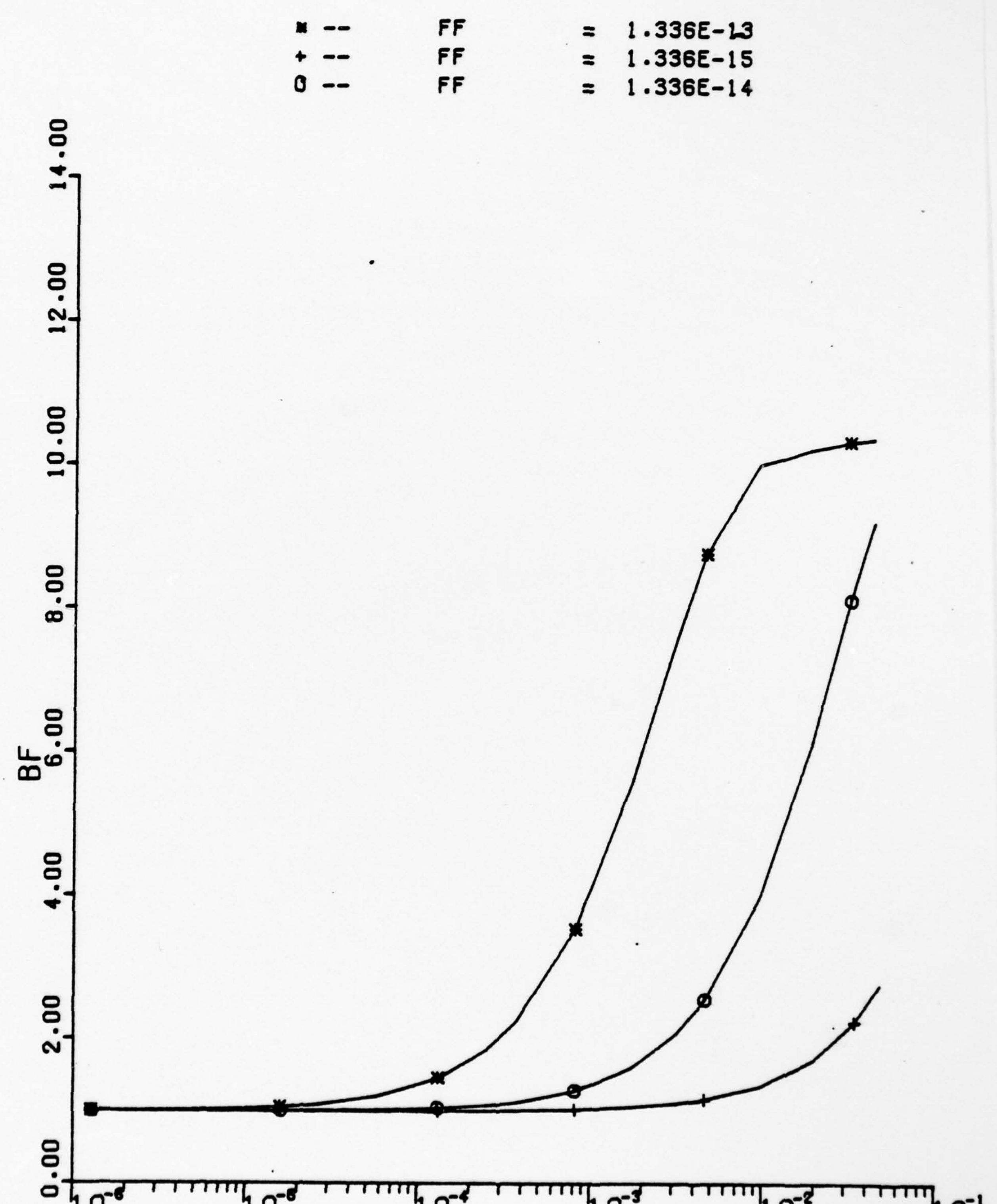


* -- VB = 1.500E+01
+ -- VB = 2.000E+01
O -- VB = 1.779E+01
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
BF
IC



* -- VB = 1.500E+01
+ -- VB = 2.000E+01
O -- VB = 1.779E+01
14.00
12.00
10.00
8.00
6.00
BF
4.00
2.00
0.00
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC


* -- VF = 2.590E-01
+ -- VF = 2.590E-03
O -- VF = 2.590E-02
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
BF
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC



* -- FF = 1.336E-13
+ -- FF = 1.336E-15
O -- FF = 1.336E-14
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
BF
$10^{-6}$
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
IC

# APPENDIX C

# PAREV (PARAMETER EVALUATION) CODE LISTING

```
      PROGRAM PAREV(INPUT,OUTPUT,TAPE5=INPUT,TAPE6,TAPE1,TAPE2)
      DIMENSION AIB(20),AIC(20),VBE(20),SCR(100),P(3)
      DIMENSION Y(2,20),Z(3,20),P1(3),PO(3)
      COMMON/PARAM/VT,IER,NE,IS,BETAO,RBO,RBB,IBB,RE,RCC,BF2,
     + VB,FF,VER,VCR
      COMMON/OPPT/XIB,XIC,XVBE
      COMMON/TEMP/THETA
      EXTERNAL ZFIND,FUNQFN,FUNEJ,FUNCJ,FUNIBE
      DIMENSION AIBR(20),AICR(20),VBER(20)
      REAL IER,IBR,IS,ISR,NE,NC,NS,IBB,L,KR
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C
C+++++PARAMETER EVALUATION CODE FOR CHOMA BIPOLAR TRANSISTOR MODEL+++
C
C THIS CODE IS AN INTERACTIVE CODE WHICH ACCEPTS ELECTRICAL AND
C GEOMETRY DATA AND GENERATES PARAMETERS FOR THE CHOMA BJT MODEL.
C THE PARAMETERS ARE USED FOR SIMULATION IN GENERAL CAD PROGRAMS
C OR IN THE COMPANION CODE(EQSOLVE) GENERATED SPECIFICALLY FOR
C THE SIMULATION OF THE CHOMA MODEL.
C   SEVERAL MODULES IN THE CODE MAY BE BYPASSED VIA DEFAULT OR
C USER OVERRIDE. HOWEVER,SOME MODULES ARE VITAL TO SUBSEQUENT
C MODULE EXECUTION:CONSULT DOCUMENTATION FOR DETAILS.
C
C    E. MOCK      TRW SYSTEMS/DSSG      SEPT. 1977
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
      NAMELIST/INDATA/RHOB,TE,AB,RBO,L,H,W,RBB,RE,RHOC,WCPRIME,XO,
     + AE,RCC,RCO,T,VTS,ISR,CSO,PHISS,CEO,PHIEO,CCO,PHICO,
     + IER,NE,IS,BETAO,IBR,NC,BETAR,VER,VCR,QFN,QRN,
     + TAUFO,TAUR,KR
      NAMELIST/TRANS/RBO,RBB,RE,RCO,BS,BC,BE,CSO,CEO,CCO,
     + PHISS,PHICO,PHIEO,ISR,IS,IER,IBR,VER,VCR,
     + NC,VT,VTS,QFN,QRN,TAUFO,TAUR,BETAO,BETAR,
     + AE,XO,WCPRIME,NE,KR,BF2,VB,VF,FF,VCE,IBB,PC
      DATA RHOB,TE,AB,RBO,L,H,W,RBB,RE,RHOC,WCPRIME,XO,AE,RCC,RCO/
     + 9E-3,1E-4,5E-7,0.,6E-5,6E-5,6E-5,0.,.5,3.25E-3,3E-4,
     + 2.7E-4,9.8E-7,7.,0./
      DATA T,ISR,IER,NE,IS,BETAO,IBR,NC,BETAR/
     +  27.,3E-12,3.2E-14,1.5,3.2E-16,55.,3E-13,1.8,1.5/
      DATA VER,VCR,GOF,GOR,QFN,QRN,TAUFO,TAUR,KR/
     +  20.,60.,0.,0.,1.5E-16,1.5E-12,1.59E-10,1.27E-9,.5/
      DATA CSO,CEO,CCO,PHISS,PHICO,PHIEO/
     + 2.E-12,9.E-13,8.E-13,.9,.9,1.2/
```

```
      DATA VT,VTS,BE2,VB,VF,EF,VCE,IBB/
     + .0259,.03,13.64,17.79,.0259,1.336E-14,5.,1.38E-4/
C**********************
C
C  READ IN THE NAMELIST DATA
C
C**********************
      REWIND 1
      READ(1,INDATA)
C**********************
C
C  PERFORM THE DEFAULT CALCULATIONS
C
C*********************
      IF(RBO.EQ.0.) RBO=RHOB*TE/AB
      IF(RBB.EQ.0.) RBB=RHOB*L/(W*H)
      IF(RCC.EQ.0.) RCC=RHOC*WCPRIME/AE
      IF(KR.NE..5) KR=(1.-AE/(AE+AB))
C*******************
C
C  ENTER THE ITERATIVE LOOP
C
C******************
   50 DISPLAY *----INPUT INDEX----*
      ACCEPT MASTER
      GO TO (50,100,200,300,400,500,600,700,800,900,1000,1100) MASTER
C******************
C
C-CODE FOR JUNCTION CAPACITANCES PARAMETER,FITTING
C
C ASSIGN ESTIMATE AND BOUNDS
C P(1)=CXO  P(2)=PHIXO  P(3)=PARASITIC CAP.
  100 P(1)=2.F-12
      PO(1)=1.E-14
      P1(1)=1E-10
      P(2)=.9
      PO(2)=.4
      P1(2)=1.5
      P(3)=1.E-12
      PO(3)=0.
      P1(3)=1E-11
      NV=2
```

```
      NP1=4
      TOL=EPS=1E-5
      ND=1
      MXIT=80
      LLK=1
      IW=0
C
C-READ IN THE EMITTER CAPAC. CURVE VALUES
C  Y(1,I)=CJE      Y(2,I)=VJE
C
      ACCEPT(1) NPT
      DO 5 I=1,NPT
      ACCEPT(1) Y(1,I),Y(2,I)
  5      CONTINUE
      DISPLAY *EMITTER JUNCTION CAPACITANCE FIT*
      CALL MINIZ(Y,SCR,P,NV,NPT,NP1,TOL,EPS,EE,ND,
     + MXIT,LLK,PO,P1,IW,FUNEJ)
      DISPLAY *CEO EST.           PHIEO EST.     PARASIT. EST.    MSE*
      DISPLAY P(1),P(2),P(3),EE
      CEO=P(1)
      PHIEO=P(2)
      GO TO 50
C*****************
C-READ IN THE COLLECTOR CAPAC. CURVE VALUES
C Y(1,I)=CJC    Y(2,I)=VJC
C*****************
 200  ACCEPT(1) NPT
      DO 7 I=1,NPT
      ACCEPT(1) Y(1,I),Y(2,I)
   7  CONTINUE
      DISPLAY *COLLECTOR JUNCTION CAPACITANCE FIT*
      DISPLAY *CO EST.           PHICO EST.      PARASIT. EST.    MSE*
      CALL MINIZ(Y,SCR,P,NV,NPT,NP1,TOL,EPS,EE,ND,
     + MXIT,LLK,PO,P1,IW,FUNCJ)
      DISPLAY P(1),P(2),P(3),EE
      CCO=P(1)
      PHICO=P(2)
      GO TO 50
C******************
C
C READ IN THE SUBSTRATE CAPAC. CURVE VALUES
C Y(1,I)=CJS     Y(2,I)=VJS
```

```
      C
      C*****************
  300 ACCEPT(1) NPT
      DO 8 I=1,NPT
      ACCEPT(1) Y(1,I),Y(2,I)
    8 CONTINUE
      DISPLAY *SUBSTRATE JUNCTION CAPACITANCE FIT*
      DISPLAY *CSO EST.    PHISS EST.   PARASIT. EST       MSE*
      CALL MINIZ(Y,SCR,P,NV,NPT,NP1,TOL,EPS,EE,ND,
     *    MXIT,LLK,PO,P1,IW,FUNCJ)
      DISPLAY P(1),P(2),P(3),EE
      CSO=P(1)
      PHISS=P(2)
      GO TO 50
      C******************
      C
      C   VER AND VCR EVALUATION CODE
      C
      C*****************
  400 DISPLAY *INPUT GOF,GOR,VBE,VBC,ICO,IEO*
      ACCEPT GOF,GOR,VBEX,VBCX,RI1,RI2
      XNUM=RI1*RI2-GOF*GOR*VBEX*VBCX
      VCR=XNUM/(GOF*(RI2+GOR*VBEX))
      VER=XNUM/(GOR*(RI1+GOF*VBCX))
      DISPLAY *VER=*,VER,*VCR=*,VCR
      GO TO 50
      C***************************
      C-RELABLE THE INPUT FOR IB-VBE FIT FOR IS/BETAO,IER,NE
      C
      C***************************
  500 ACCEPT (1) NCTF,VCEX
      DO 10 I=1,NCTF
      ACCEPT(1) AIB(I),AIC(I),VBE(I)
   10 CONTINUE
            DO 12 I=1,NCTF
            Y(1,I)=AIB(I)
            Y(2,I)=VBE(I)
   12       CONTINUE
      C---SET UP GUESSES AND OTHER CONSTANTS
      C
      P(1)=1E-14
      P(2)=27
```

```
      P(3)=1F-15
      PO(1)=PO(3)=0.
      PO(2)=20
      P1(1)=P1(3)=1.
      P1(2)=40
      NV=2
      NP=3
      NP1=4
      TOL=EPS=1E-5
      ND=1
      MXIT=80
      LLK=1
      TW=-0
C----CALCULATE TEMPERATURE ESTIMATE FROM IC DATA
      NCTM1=NCTF-1
      DISPLAY *POINT TO POINT TEMPERATURE(DEG. C)*
      DO 20 I=1,NCTM1
      J=I+1
      T=-273+11594.2*(Y(2,J)-Y(2,I))/ALOG(AIC(J)/AIC(I))
            THI=11594.2*Y(2,I)/(T+273.)
 20         DISPLAY I,J,T
      DISPLAY * INPUT TEMP. ESTIMATE(DEG. C)*
      ACCEPT(5) T
      THETA=11594.2/(T+273)
            VT=1./THETA
C**
C  OUTPUT THE CALCULATED VALUES OF IS BASED ON AN INPUT
C VALUE OF TEMPERATURE
C**
      DISPLAY *POINT          IS*
      DO 25 I=1,NCTF
      IS=AIC(I)/EXP(VBE(I)/VT)
      DISPLAY I,IS
 25   CONTINUE
C--ACCEPT THE IS ESTIMATE
      DISPLAY *ENTER THE IS ESTIMATE*
      ACCEPT IS
C**********************
C----START THE 3-PARAMETER MOVING FIT
C---START WITH 4 POINTS AND INCREASE NO. OF POINTS IN FIT
       DISPLAY *NPTS          IER             NE              IS/BO      *,
     + *     MSE*
```

```
      DO 30 NNC=4,NCTE
      CALL MINIZ(Y,SCR,P,NV,NNC,NP1,TOL,EPS,
     + EE,ND,MXIT,LLK,PO,P1,IW,FUNIBE)
      RMEP=EE/FLOAT(NNC)
      NE=THETA/P(2)
   30 DISPLAY NNC,P(1),NE,P(3),EE
      DISPLAY *INPUT IER,NE,BETAO ESTIMATE*
      ACCEPT IER,NE,BETAO
      GO TO 50
C*******************
C
C  EVALUATE THE REVERSE DIODE CHARACTERISTICS:IBR,NC,IS/BETAR
C
C*******************
  600 ACCEPT(1) NCT,XX
      DO 71 I=1,NCT
      ACCEPT(1) Y(1,I),XX,Y(2,I)
   71 CONTINUE
C--START THE 3 PARAMETER MOVING FIT
C--START WITH 4 POINTS AND INCREASE NO. OF POINTS
      DISPLAY *NPTS         IBR               NC               IS/BR         *,
     + *     MSE*
      DO 81 NNC=4,NCT
      CALL MINIZ(Y,SCR,P,NV,NNC,NP1,TOL,EPS,
     + EE,ND,MXIT,LLK,PO,P1,IW,FUNIBE)
      RMEP=EE/FLOAT(NNC)
      NC=THETA/P(2)
      DISPLAY NNC,P(1),NC,P(3),EE
   81 CONTINUE
      DISPLAY *INPUT IBR,NC,BETAR ESTIMATES*
      ACCEPT IBR,NC,BETAR
      GO TO 50
C*****************************
C
C-EVALUATE THE BASE PUSHOUT PARAMETERS-BF2,VB,FF
C*****************************
  700 DISPLAY *INPUT 1 FOR SINGLE STRIPE,2 FOR DOUBLE*
      ACCEPT NST
      RNST=FLOAT(NST)
      IBB=RNST*RNST*2.*VT/RBB
      DISPLAY *INPUT 4-POINT BASE PUSHOUT DATA*
      DISPLAY *INPUT FT1,FT2,FT3,FT4,IC1,IC3,VCE1,VCE4*
```

```
      ACCEPT FT1,FT2,FT3,FT4,RIC1,RIC3,VCE1,VCE4
C--CALCULATE BF(SMALL) FROM POINTS 1-2
      BF2=FT1/FT2-1.
C-CALCULATE VB FROM POINTS 3-4
C------CALC VE VC (INTERNAL) AT 3-4
   99 XBF3=FT1/FT3
      CALL VINT(XBF3,RIC3,VCE1,VE3,VC3,AIB,AIC,VBE,NCT)
      XBF4=FT1/FT4
      CALL VINT(XBF4,RIC3,VCE4,VE4,VC4,AIB,AIC,VBE,NCT)
      VB=(VC3-VC4)/(ALOG(XBF3-1.)-ALOG(XBF4-1.))
C--CALCULATE FF FROM POINT 4
      FF=-ALOG(1.-(XBF4-1.)/(BF2*EXP(VC4/VB)))/(EXP(VE4/VT)-1.)
      DISPLAY *BF2=*,BF2,*VB=*,VB,*FF=*,FF
      GO TO 50
C
C***********************
C---QFN EVALUATION CODE-----
C***********************
C REORDER THE INPUT ARRAYS FOR QFN CALCULATIONS
  800 DO 51 I=1,NCTF
      NB=NCTF-I+1
      Z(1,I)=AIC(NB)
      XIB=AIB(NB)
C-CALL GRTM TO EVALUATE Z FOR THE DATA POINT
      CALL GRTM(1,VALU,1,50,ZFIND,0.1,E-6)
      ZZZ=VALU
C Z(2,I)=VEPRIME FOR DATA POINT
      RB=RBB*(TAN(ZZZ)-ZZZ)/(4.*ZZZ*(TAN(ZZZ)**2))
      Z(2,I)=VBE(NB)-XIB*(RBO+RB)+RB*IER*EXP((VBE(NB)-XIB*RBO)/(NE*VT))
      Z(2,I)=Z(2,I)-RE*(XIB+Z(1,I))
C APPROXIMATE RC BY .5*RCC(LOW CURRENT VALUE) FOR VCPRIME EVALUATION
C Z(3,I)=VCPRIME
      Z(3,I)=Z(2,I)+(XIB+Z(1,I))*RE+Z(1,I)*.5*RCC-VCEX
   51 CONTINUE
C
C--PERFORM NONLINEAR LEAST SQUARES FIT FOR QFN USING THE IC EQN.
C--FITTED TO VARIABLES VEPRIME AND VCPRIME
C
C        START WITH TWO HIGHEST INJECTION POINTS AND INCREASE
C        ASSIGN EESTIMATE AND BOUNDS FOR QFN
      P(1)=1E-15
      PO(1)=0.
```

```
      P1(1)=1.
      NV=3
      NP1=2
      TOL=EPS=1E-5
      ND=1
      MXIT=80
      LLK=1
      IW=0
      DISPLAY *QFN FIT*
      DISPLAY *NPTS*,*   QFN EST.*,*   MEAN SQ.ERROR*,*      MSE/NPTS*
      DO 70 NNC=2,NCTF
      CALL MINIZ(2,SCR,P,NV,NNC,NP1,TOL,EPS,
     +  EE,ND,MXIT,LLK,PO,P1,IW,FUNQFN)
      RMEP=EE/FLOAT(NNC)
      DISPLAY NNC,P(1),EE,RMEP
   70 CONTINUE
      DISPLAY *INPUT QFN ESTIMATE*
      ACCEPT QFN
      GO TO 50
C********************
C
C  CALCULATE TAUFO FROM MAXIMUM FT DATA POINT
C
C********************
  900 CJE=CEO/(1.-.7/PHIEO)**.5
      CJC=CCO/(1.-(.7-VCE1)/PHICO)**.333333
      TAUFO=(.15915/FT1-(CJE+CJC*(1.+RIC1*RCC/VT))*VT/RIC1)*
     +  (1.+(.7-VCE1)/VCR)**2
      DISPLAY *TAUFO=*,TAUFO
      GO TO 50
C*******************
C
C  TAUR CALCULATION FROM SATURATION TIME DATA
C
C*******************
 1000 DISPLAY *INPUT IBF,IBR,ICF,TS*
      ACCEPT RB1,RB2,RC1,RTS
      TSAT=RTS/ALOG((RB1+RB2)/(RC1/BETAO+RB2))
      TAUR=TSAT*(1.+1./BETAR-BETAO/(BETAO+1.))-
     + (BETAO*(BETAR+1.)/(BETAR*(BETAO+1.)))*TAUFO
      QRN=QFN*TAUR/TAUFO
      DISPLAY *TSAT=*,TSAT,*TAUR=*,TAUR,*QRN=*,QRN
```

```
      GO TO 50
C********************
C
C  OUTPUT THE VALUES OF MODEL PARAMETERS TO UNIT (2)
C
C********************
 1100 CONTINUE
      VF=VT
      BS=BC=1./3.
      BF=0.5
      PC=RHOC
      WRITE(2,TRANS)
      END
      SUBROUTINE ZFIND(Z,FZ)
C--ZFIND CALCULATES Z GIVEN IB,IBB IN CONJ. WITH GRTM ROOTFINDER
      COMMON/PARAM/SKIP(7),IBB,SKIP2(7)
      COMMON/OPPT/IB,SKIP3(2)
      REAL IBB,IB
      FZ=Z*TAN(Z)-(IB/IBB)
      RETURN
      END
      SUBROUTINE VINT(XBF,RICIN,VCEIN,VEOT,VCOT,AIB,AIC,VBE,NCT)
C------SUBR. CALCULATES INTERNAL EMITTER AND COLLECTOR VOLTAGES GIVEN
C------     ICIN=COLLECTOR CURRENT
C------    VCEIN=COLLECTOR - EMITTER VOLTAGE
C---------      REMAINING DATA IS FROM THE PREVIOUSLY INPUT
C------     IC,IB,VBE TABLES AND MODEL PARAMETERS
      COMMON/PARAM/VT,IER,NE,IS,BETAO,RBO,RBB,IBB,RE,RCC,BF2,
     +  VB,FF,VER,VCR
      COMMON/OPPT/XIB,XIC,XVBE
      EXTERNAL ZFIND
      REAL IFR,NE,IS,IBB
C-FIND IB BY INTERPOLATION OF IC
      CALL INTERP(AIC,AIB,NCT,RICIN,XIB)
C-FIND VBE BY INTERPOLATION
      CALL INTERP(AIC,VBE,NCT,RICIN,XVBE)
C-FIND RB VIA ROOT FINDER ROUTINE
      CALL GRTM(1,VALU,1,50,ZFIND,0,1.E-6)
      Z=VALU
      RB=RBB*(TAN(Z)-Z)/(4.*Z*(TAN(Z)**2))
      VEOT=XVBE-XIB*(RBO+RB)+RB*IER*EXP((XVBE-XIB*RBO)/(NE*VT))
      VEOT=VEOT-RE*(XIB+RICIN)
```

```
C-FIND RC BY BASE PUSHOUT EVALUATION
      RC=AMAX1(0.,RCC*(1.-SQRT(XRF-1.)/BF2))
   90 VCOT=VEDT+(XIB+RICIN)*RE*RICIN*RC-VCEIN
      RETURN
      END
      SUBROUTINE INTERP(X,Y,N,VAL,OUTP)
C-LINEAR INTERPOLATION ROUTINE
      DIMENSION X(1),Y(1)
      IF(VAL.LT.X(1))WRITE(6,100) VAL,X(1)
      IF(VAL.GT.X(N))WRITE(6,110) VAL,X(N)
      I=0
   10 I=I+1
      XT=X(I)
      IF(XT-VAL) 10,20,30
C-EXACT VALUE IN TABLES
   20 OUTP=Y(I)
      RETURN
C-INTERPOLATION REQUIRED
   30 OUTP=Y(I-1)+(VAL-X(I-1))*(Y(I)-Y(I-1))/(X(I)-X(I-1))
      RETURN
  100 FORMAT(*INTERP ROUTINE IS OFF THE LOW END FOR INPUT=*,E10.4,
     +  *AND MIN TABLE VALUE=*,E10.4)
  110 FORMAT(*INTERP ROUTINE IS OFF THE HIGH END FOR INPUT=*,E10.4,
     +  *AND MAX TABLE VALUE=*E10.4)
      END
      SUBROUTINE GRTM(N,C,IN,MAXIT,AUX,KNN,EPS)                  GRTM     1
      DIMENSION C(1),T(3),X(3)                                   GRTM     2
      EPS1=ABS(EPS)                                              GRTM     3
      IF(EPS1.EQ.0.) EPS1=1.0E-6                                 GRTM     4
      L1=KNN+1                                                   GRTM     5
      L2=KNN+N                                                   GRTM     6
      IOUT=IN                                                    GRTM     7
C                                                                GRTM     8
C     BEGIN LOOP TO FIND N ROOTS                                 GRTM     9
C                                                                GRTM    10
      DO 170 L=L1,L2                                             GRTM    11
      T(1)=C(L)                                                  GRTM    12
      H=-1.0                                                     GRTM    13
      IF(T(1).NE.0.) H=-T(1)/10.                                 GRTM    14
      D=-.5                                                      GRTM    15
      J1=MAXIT                                                   GRTM    16
  100 MAXJ=J1                                                    GRTM    17
```

```
      RT=T(1)
      IF(MAXJ.EQ.0) GO TO 155
      T(2)=T(1)-H
      T(3)=T(1)+H
C
C     BEGIN ITERATIONS TO FIND ONE ROOT
C
      DO 150 J=1,MAXJ
      CALL AUX(RT,FRT)
      FPRT=FRT
      IF(L.EQ.1) GO TO 110
C
C     EVALUATE FP(RT)
C
      DO 105 I=2,L
      DEN=RT-C(I-1)
      IF(J.GT.3) GO TO 105
      J1=J1-1
      IF(ABS(DEN).GE.1.E-20) GO TO 105
C
C     RESTART ITERATION WHEN ANY OF THE THREE STARTING
C          VALUES ARE TOO CLOSE TO A PREVIOUS ROOT
C
      IF(IOUT.EQ.0) WRITE(6,500)L
      T(1)=T(1)+.001
      GO TO 100
  105 FPRT=FPRT/DEN
  110 IF(IOUT.EQ.0) WRITE(6,500)L,RT,FRT,FPRT
C
C     RT IS A ROOT IF F(RT) AND FP(RT) ARE BOTH SMALL
C
      IF((ABS(FRT).LT.1.E-20).AND.(ABS(FPRT).LT.1.E-20)) GO TO 160
      IF(J.GT.3) GO TO 115
      X(J)=FPRT
      IF(J.EQ.3) GO TO 114
      RT=T(J+1)
      GO TO 150
  114 RT=T(1)
      GO TO 125
  115 IF(ABS(FPRT).LT.ABS(X(1)*10.)) GO TO 120
C
C     FP(RT) IS TOO LARGE---REDUCE H AND TRY AGAIN
```

```
C                                                                GRTM    60
      DI=DI*.5                                                   GRTM    61
      H=H*.5                                                     GRTM    62
      RT=RT-H                                                    GRTM    63
      GO TO 150                                                  GRTM    64
C                                                                GRTM    65
C     MOVE DATA                                                  GRTM    66
C                                                                GRTM    67
  120 X(3)=X(2)                                                  GRTM    68
      X(2)=X(1)                                                  GRTM    69
      X(1)=FPRT                                                  GRTM    70
      D=DI                                                       GRTM    71
C                                                                GRTM    72
C     CALCULATE NEXT APPROXIMATION                               GRTM    73
C                                                                GRTM    74
  125 A=1.0+D                                                    GRTM    75
      B=X(3)*D*D-X(2)*A*A+X(1)*(A+D)                             GRTM    76
      DEN=B*B-(4.0*X(1)*D*A)*(X(3)*D-X(2)*A+X(1))                GRTM    77
      DI=-2.0*X(1)*A                                             GRTM    78
      IF(DEN.LE.0.) GO TO 130                                    GRTM    79
      DEN=SQRT(DEN)                                              GRTM    80
      IF(B.NE.0.) DEN=B+SIGN(DEN,B)                              GRTM    81
      GO TO 135                                                  GRTM    82
  130 IF(IOUT.EQ.0) WRITE(6,500)L,DEN                            GRTM    83
      IF(B.EQ.0.) GO TO 140                                      GRTM    84
      DEN=B                                                      GRTM    85
  135 DI=DI/DEN                                                  GRTM    86
  140 H=DI*H                                                     GRTM    87
      RT=RT+H                                                    GRTM    88
      IF (ABS(H).LE.EPS1*ABS(RT)) GO TO 155                      GRTM*1   1
  150 CONTINUE                                                   GRTM    90
  155 CALL AUX(RT,FRT)                                           GRTM    91
  160 C(L)=RT                                                    GRTM    92
      IF(IOUT.EQ.0) WRITE(6,501)L,RT,FRT                         GRTM    93
  170 CONTINUE                                                   GRTM    94
      IF(IOUT.EQ.0) WRITE(6,502)                                 GRTM    95
      RETURN                                                     GRTM    96
  500 FORMAT(I3,3E20.8)                                          GRTM    97
  501 FORMAT(I3,2E20.8/1H )                                      GRTM    98
  502 FORMAT(1H1)                                                GRTM    99
      END                                                        GRTM   100
      SUBROUTINE MINIZ(X,A,P,NV,NC,NP1,TOL,EPS,
```

```
     + EE,ND,MXIT,LLK,PO,P1,IW,FUN)
C         SUBROUTINE MINIZ FOR BMD07R          APRIL 4, 1966
      DIMENSION A(NP1,NP1),X(NV,NC),P(100),FP(100),D(100),PO(100),P1(100
     1),B(10)
C
      DIMENSION PPO(100)
C
C
C
      IF(IW.EQ.0)C=1.0
      NP=NP1-1
      MNAIL = 10
      NAIL = 0
      DO 557 I=1,NP
  557 PPO(I)=P(I)
C
      EPS1=5.*EPS+1.
      WRITE(6,23)(PO(I),I=1,NP)
   23 FORMAT(*1MINIMA*,15X,1P9E12.4/(22X,1P9E12.4))
      WRITE(6,22)(P1(I),I=1,NP)
   22 FORMAT(*0MAXIMA*,15X,1P9E12.4/(22X,1P9E12.4))
      WRITE(6,195)
  195 FORMAT(*0ITERATION    ERROR     PARAMETERS*/14X,*MEAN*/14X,*SQUARE
     1*)
  194 LLL=5
      LIT=0
      HU=NC
      H=0.
      LLLL=5
      EO=7.2E75
      DO 556 I=1,NP
  556 P(I)=PPO(I)
      FNC=NC-NP
   29 DO 85 I=1,NP1
      DO 85 J=1,I
   85 A(I,J)=0.
      DO 2 L=1,NC
C     CALL FUN(F(L),FP,X(1,L),P,LLK)
      CALL FUN(Q,FP,P,X(1,L))
      FP(NP1)=X(ND,L)-Q
      IF(IW.NE.0)C=X(IW,L)
      IF(C.LT.(1.E-20)) GO TO 2
```

```
      DO 1 I=1,NP1
      FPIC=FP(I)*C
      DO 1 J=1,I
    1 A(I,J)=A(I,J)+FPIC*FP(J)
    2 CONTINUE
      EE=A(NP1,NP1)/FNC
    6 IF(EE.LE.EO) GO TO 871
      NAIL=NAIL+1
      IF(NAIL.GT.MNAIL) GO TO 871
      DO 872 I=1,NP
      P(I)=PPO(I)+D(I)/2.
  872 D(I)=D(I)/2.
      GO TO 29
C
C
  871 WRITE(6,198)LIT,NAIL,EE,(P(I),I=1,NP)
  198 FORMAT(I6,1X,I2,1X,1P10E12.4/(22X,1P9E12.4))
      NAIL=0
 8191 LIT=LIT+1
      CALL STEP(A,D,P,PO,P1,NP1,TOL)
      IF(LIT.GT.MXIT) GO TO 200
      IF(EE.EQ.0.) GO TO 470
      PC=1.
      IF(EO.NE.7.2E75) PC=ABS((EO-EE)/EE)
      EO=EE
      IF(PC.LT.EPS) GO TO 100
      LLL=LLLL
  121 DO 28 I=1,NP
      PPO(I)=P(I)
   28 P(I)=P(I)+D(I)
      GO TO 29
  200 WRITE (6,201)
  201 FORMAT(30HOTHE PROCESS IS NOT CONVERGING)
      GO TO 470
  100 LLL=LLL-1
      IF(LLL.NE.0) GO TO 121
  470 DO 778 I=1,NP
  778 FP(I)=SQRT(ABS(A(I,I)*EE))
      WRITE (6,779) (FP(I),I=1,NP)
  779 FORMAT(*OASYMPTOTIC STANDARD DEVIATIONS OF THE PARAMETERS*//
     X(10X,1P10E12.4))
      DO 841 I=1,NP
```

```
      FP(I)=SQRT(ABS(A(I,I)))
      DO 841 J=1,I
  841 A(J,I)=A(I,J)
      WRITE(6,774)
  774 FORMAT(*0ASYMPTOTIC CORRELATION MATRIX OF THE PARAMETERS*)
      L1=0
  371 L0=L1+1
      L1=MIN0(NP,L1+10)
      WRITE(6,372)(L,L=L0,L1)
  372 FORMAT(*0*,10I12)
      DO 842 I=1,NP
      K=0
      DO 373 J=L0,L1
      K=K+1
      IF(FP(I).EQ.0.0.OR.FP(J).EQ.0.0.OR.A(I,J).EQ.0.0)GO TO 843
      B(K)=A(I,J)/(FP(I)*FP(J))
      GO TO 373
  843 B(K)=0.0
  373 CONTINUE
  842 WRITE(6,374)I,(B(J),J=1,K)
  374 FORMAT(I4,2X,10F12.5)
      IF(L1.NE.NP)GO TO 371
 1515 WRITE(6,553)
  553 FORMAT(*1CASE        F              Y-F  STANDARD            VARIABLES
     1*/30X,*DEVIATION*/30X,*OF ESTIMATE*)
      DO 551 L=1,NC
      SDEST=0.0
      CALL FUN(Q,FP,P,X(1,L))
      DO 24 I=1,NP
      DO 24 J=1,NP
   24 SDEST=SDEST+FP(I)*FP(J)*A(I,J)
      SDEST=SQRT(SDEST*EE)
      TT=X(ND,L)-Q
  551 WRITE(6,552)L,Q,TT,SDEST,(X(I,L),I=1,NV)
  552 FORMAT(1X,I4,10F12.5/(41X,7F12.5))
      RETURN
      END
      SUBROUTINE STEP(A,D,P,P0,P1,NP1,TOL)
C         SUBROUTINE STEP FOR BMD07R         APRIL 4, 1966
      DIMENSION A(NP1,NP1),V(100),D(100),IN(100),P0(100),P1(100),P(100)
C
      NP=NP1-1
```

```
      DO 20 I=1,NP1
      V(I)=SQRT(A(I,I))
      DO 20 J=1,I
      IF (V(I)*V(J).EQ.0.) GO TO 212
      A(I,J)=A(I,J)/(V(I)*V(J))
      GO TO 20
  212 A(I,J)=0.
   20 CONTINUE
      DO 2 I=1,NP
2     IN(I)=0
8     K=0
      R=0.
      DO 1 I=1,NP
      IF(IN(I).NE.0 .OR. A(I,I).LE.TOL) GO TO 1
      Q=A(NP1,I)*A(NP1,I)/A(I,I)
      IF(Q.LT.R) GO TO 1
      K=I
      R=Q
1     CONTINUE
      IF(K.EQ.0) GO TO 3
      C=-1.
4     DO 5 I=1,K
      D(I)=A(K,I)
5     A(K,I)=0.
      PP=D(K)
      DO 6 I=K,NP1
      D(I)=A(I,K)
6     A(I,K)=0.
      D(K)=C
      IN(K)=IN(K)+1
      DO 7 I=1,NP1
      IF (PP.EQ.0..OR.D(I).EQ.0.) GO TO 24
      Y=D(I)/PP
      GO TO 25
   24 Y=0.
   25 CONTINUE
      DO 7 J=1,I
7     A(I,J)=A(I,J)-D(J)*Y
      GO TO 8
3     R=1.
      DO 9 I=1,NP
      IF(IN(I).NE.1) GO TO 9
```

```
      IF (V(I).EQ.0.) GO TO 15
      D(I)=A(NP1,I)*V(NP1)/V(I)
C
C
C
   16 IF (D(I).EQ.0.) GO TO 17
      H=AMAX1((PO(I)-P(I))/D(I),(P1(I)-P(I))/D(I))
      GO TO 18
   15 D(I)=0.0
 17   H=1.
   18 CONTINUE
      IF(H.GE.R) GO TO 9
      R=H
      K=I
 9    CONTINUE
      C=1.
      IF(R.LE.TOL) GO TO 4
      DO 10 I=1,NP
      IF(IN(I).NE.1) GO TO 11
      D(I)=D(I)*R
      DO 21 J=1,I
      IF ((V(I)*V(J)).EQ.0.0) GO TO 30
      A(I,J)=-A(I,J)/(V(I)*V(J))
      GO TO 21
   30 A(I,J)=0.
 21   A(J,I)=A(I,J)
      GO TO 10
 11   D(I)=0.
      DO 22 J=1,NP
      A(I,J)=0.
 22   A(J,I)=0.
 10   CONTINUE
      RETURN
      END
      SUBROUTINE FUNIBE(F,D,P,X)
C
C-THIS ROUTINE PROVIDES FUNCTION AND DERIVATIVE VALUES FOR
C- THE EVALUATION OF IER,NE,IS/BO USING IB-VBE VALUES
C             E. MOCK TRW SYSTEMS    SEPT 1977
C
             COMMON/TEMP/THETA
      DIMENSION X(1),D(1),P(1)
```

```
      F=P(1)*(EXP(P(2)*X(2))-1.)+P(3)*(EXP(THETA*X(2))-1.)
       D(1)=EXP(P(2)*X(2))-1.
       D(2)=P(1)*X(2)*EXP(P(2)*X(2))
       D(3)=EXP(THETA*X(2))-1.
      RETURN
      END
      SUBROUTINE FUNEJ(F,D,P,X)
C
C-THIS ROUTINE PROVIDES FUNCTION AND DERIVATIVES FOR EVALUATION
C OF CJEO AND PHIEO VIA CJE FIT.     E. MOCK  TRW SYSTEMS  AUG. 1977
C
C NOTE: BE=1/2 PERMANENT ASSIGNMENT
C
      DIMENSION D(1),X(1),P(1)
      F=P(1)/((1.-X(2)/P(2))**.5)+P(3)
      D(1)=F/P(1)
      D(2)=-P(1)*.5*X(2)/(P(2)*P(2)*(1.-X(2)/P(2))**1.5)
      D(3)=1.
      RETURN
      END
      SUBROUTINE FUNCJ(F,D,P,X)
C
C-THIS ROUTINE PROVIDES FUNCTION AND DERIVATIVES FOR EVALUATION
C OF CJCO AND PHICO VIA CJC FIT.     E. MOCK  TRW SYSTEMS  AUG. 1977
C
C NOTE: BC=1/3 PERMANENT ASSIGNMENT
C
      DIMENSION D(1),X(1),P(1)
      F=P(1)/((1.-X(2)/P(2))**.333333)+P(3)
      D(1)=F/P(1)
      D(2)=-P(1)*.333333*X(2)/(P(2)*P(2)*(1.-X(2)/P(2))**1.333333)
      D(3)=1.
      RETURN
      END
      SUBROUTINE FUNQFN(F,D,P,X)
      COMMON/PARAM/VT,IER,NE,IS,BETAO,RBO,RBB,IBB,RE,RCC,BF2,VB,
     + FF,VER,VCR
C     THIS SUBROUTINE PROVIDES FUNCTION AND DERIVATIVES FOR
C     EVALUATION OF QFN FOR COLLECTOR CURRENT FIT BY ROUTINE
C     MINIZ         E. MOCK     TRW SYSTEMS   AUG.,1977
C-----------------------------------------------------
      DIMENSION D(1),P(1),X(1)
```

```
      REAL IER,NE,IS,IBB,LMB2
      FFX=-FF*(EXP(X(2)/VT)-1.)
            LMB2=(1.+X(2)/VER+X(3)/VCR)/2.
      BF=1.+BF2*EXP(X(3)/VB)*(1.-EXP(FFX))
      XSQR=SQRT(LMB2*LMB2+BF*P(1)*EXP(X(2)/VT))
      RK1=IS*EXP(X(2)/VT)
      F=RK1/(LMB2+XSQR)
      D(1)=(-RK1*BF*EXP(X(2)/VT))/(2.*(LMB2+XSQR)*XSQR)
      RETURN
      END
      SUBROUTINE ATOF(A,N,F)
      DIMENSION A(1)
      LOGICAL BLANK
      BLANK=.TRUE.
      S=1.0
      NUMB=0
      TEN=1.0
      DIV=1.0
      DO 10 I=1,N
      L=INTCHR(A,I)
      IF(L.EQ.36) GO TO 10
      BLANK=.FALSE.
      IF(L.NE.38) GO TO 2
      S=-1.0
      GO TO 10
    2 IF(L.NE.44) GO TO 4
      TEN=10.0
      GO TO 10
    4 IF(L.GT.9) GO TO 9
      NUMB=NUMB*10+L
      DIV=DIV*TEN
    9 CONTINUE
   10 CONTINUE
      IF(BLANK)RETURN
      F=S*FLOAT(NUMB)/DIV
      RETURN
      END
      FUNCTION INTCHR(STRING,N)
      DIMENSION SEQ(50),STRING(1),EBCD(5)
      DATA SEQ/1H0,1H1,1H2,1H3,1H4,1H5,1H6,1H7,1H8,1H9,
     X          1HA,1HB,1HC,1HD,1HE,1HF,1HG,1HH,1HI,1HJ,
     X          1HK,1HL,1HM,1HN,1HO,1HP,1HQ,1HR,1HS,1HT,
```

```
      X              1HU,1HV,1HW,1HX,1HY,1HZ,1H ,1H+,1H-,1H*,
      X              1H/,1H(,1H),1H,,1H.,1H*,1H=,1H$,1H ,1H /
       DATA EBCD/1H+,1H(,1H),1H*,1H=/
       CALL GETCHR(STRING,N,CHR)
       IF (CHR.NE.SEQ(37)) GO TO 2
       INTCHR = 36
       GO TO 10
     2 DO 1 I=1,48
       IF(SEQ(I).EQ.CHR) GO TO 9
     1 CONTINUE
       I=51
       IF(EBCD(1).EQ.CHR) I=38
       IF(EBCD(2).EQ.CHR) I=42
       IF(EBCD(3).EQ.CHR) I=43
       IF(EBCD(4).EQ.CHR) I=46
       IF(EBCD(5).EQ.CHR) I=47
     9 INTCHR=I-1
    10 RETURN
       END
       SUBROUTINE GETCHR(A,N,C)
       DIMENSION A(N)
       DIMENSION FMAT(6)
       DATA FMAT/4H(A1),7H(1X,A1),7H(2X,A1),7H(3X,A1),7H(4X,A1),
     +  7H(5X,A1)/
       DECODE(10,FMAT(N),A)C
       RETURN
       END
```

# APPENDIX D

# TRANSIENT RADIATION RECOVERY CHARACTERISTICS OF BIPOLAR JUNCTION TRANSISTORS

## TRANSIENT RADIATION RECOVERY CHARACTERISTICS OF BIPOLAR JUNCTION TRANSISTORS

Dr. John Choma, Jr.
Senior Member, IEEE

ABSTRACT

This paper addresses the transient recovery characteristics of a bipolar junction transistor subjected to a saturating dose-rate radiation event. An estimate of the maximum recovery time is derived in terms of parameters typically listed on device specification sheets, physical device characteristics, and circuit parameters. Performance degradation due to high-injection phenomena is also addressed.

### 1.0 INTRODUCTION

Saturation is invariably incurred by a bipolar junction transistor exposed to an ionizing dose rate event, particularly if the transistor in question conducts large quiescent collector current or if the collector of the device is terminated in a large resistance. Since a saturated transistor behaves as a short-circuit in the sense that it is incapable of responding to input signal excitation, the time required by the device to recover from the saturating excitation is clearly a critical measure of circuit performance. For example, this recovery certainly influences the frequency response of a linear system and in digital circuitry, it degrades the nominal propagation delay. If the transistor in question is in a power supply, excessive recovery requirements may well lead to catastrophic circuit or system failure.

This paper addresses the problem of generating realistic worst case estimates of recovery time in saturated transistors. The equations are cast as functions of device and circuit parameters. Although the results are predicated on simple modeling techniques, a semi-quantitative account of complex high-injection phenomena is offered to refine the first-order results obtained.

## 2.0 PHOTOCURRENT RESPONSE

Figure (1) depicts a simplified schematic diagram of a bipolar junction transistor (BJT) subjected to a gamma dose rate or gamma dot ($\dot{\gamma}$) event. The gamma dot event is modeled electrically by a collector-to-base photocurrent source, $i_{pp}(t)$. As shown in Figure (2), photocurrent $i_{pp}(t)$ is a simple current pulse of amplitude $I_{PP}$ and width $T_P$.

Let it be assumed that for all steady-state conditions corresponding to $i_{pp}(t) = 0$, the effective source current, $I_S$, is of a magnitude appropriate to operation of the BJT in the linear active region of its static characteristic curves. Thus, for time $t < -T_P$, the collector current is $i_c(t) = I_{CA}$. The corresponding base current, $i_b(t)$, is

$$I_{BA} = I_{CA}/h_{FE}, \tag{1}$$

where $h_{FE}$ is the static forward current transfer ratio of the bipolar device.

At $t = -T_P$, the collector current, $i_c(t)$, rises toward its saturated value, say $I_{CS}$, in response to abrupt photocurrent excitation. By inspection of Figure (1), this saturated value of collector current is

$$I_{CS} = \frac{V_{CC} - V_{CSAT}}{R_C} - I_{PP}, \tag{2}$$

where $V_{CSAT}$ is the collector-to-emitter saturation voltage. The corresponding base current is not linearly related to $I_{CS}$ by an expression of the form of (1) since $h_{FE}$ is defineable only for the case of transistor operation in its linear active region. Accordingly, if constant collector current in the amount of $I_{CS}$ is achieved in the time frame, $-T_P < t < 0$, the base current, $I_{BS}$, is

$$I_{BS} = I_S + I_{PP} - \frac{V_{BSAT}}{R_{BB}}. \tag{3}$$

In (3), $V_{BSAT}$ is the value of base-emitter voltage, $v_{BE}(t)$, under steady-state saturated conditions.

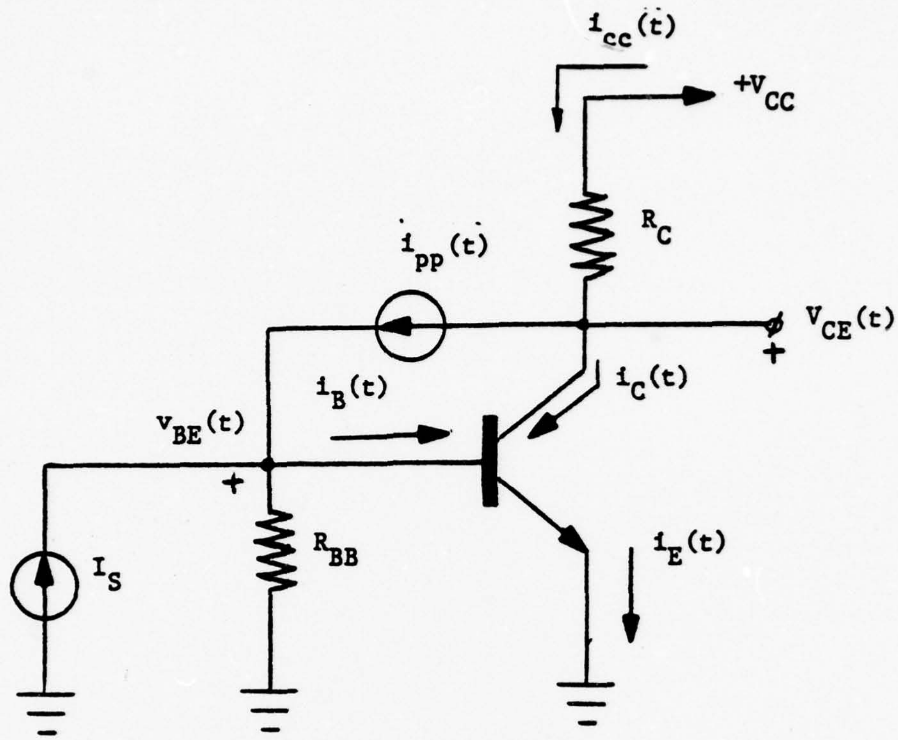



Figure (1). Schematic Diagram of Circuit Used For Radiation Storage Time Analysis

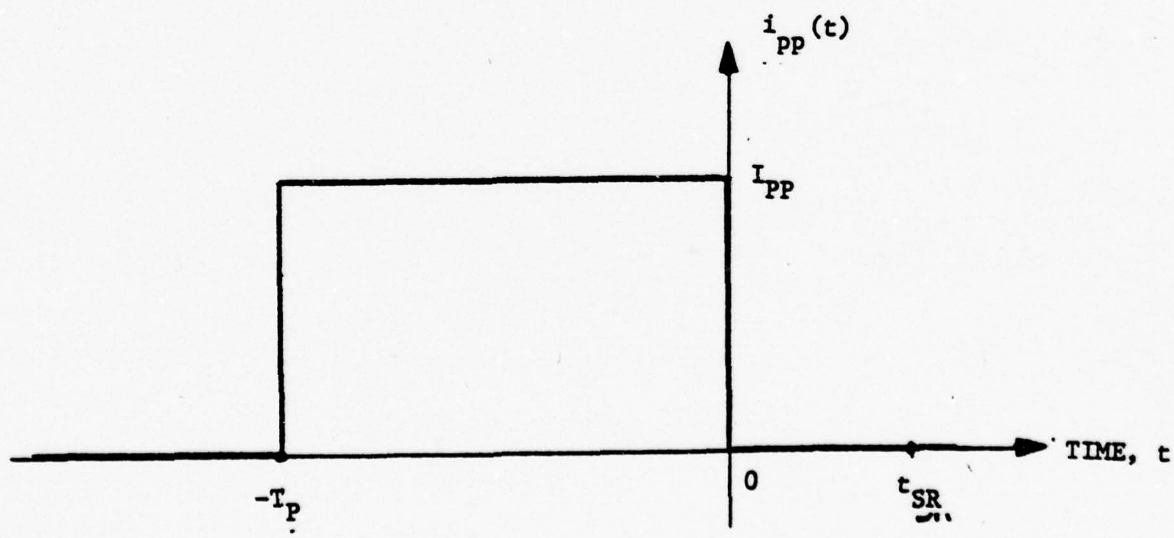



Figure (2). Time Domain Variation of Photocurrent Source, $i_{pp}(t)$

Assuming that the transistor in Figure (1) is indeed saturated in the neighborhood of $t < 0$, both device junctions are forward biased. Resultantly, a substantial amount of charge is stored in the base. The presence of excess base charge, which is viewed herewith as the difference between total base charge and the charge that accrues if only the base-emitter junction is forward biased, precludes an immediate response of the collector current to the instantaneous termination of the photocurrent pulse. The time required to reduce the excess charge to zero or equivalently, the time required to re-establish non-forward bias across the base-collector junction, is termed the "radiation storage time," $t_{SR}$.

The concept of radiation storage time is best appreciated by an investigation of Figure (3), which conceptually plots the distribution of charge injected into the base under varying bias conditions. Figure (3a) pertains to a BJT operating in its linear active region. Charge $Q_{BO}$, which is symbolized by the area of the cross-hatched region, is the equilibrium minority carrier distribution evidenced in the base under zero bias conditions. If the base width (W) is small, the charge profile arising out of forward injection across the base-emitter junction can be approximated by a straight line. This line has negative slope, since the reverse bias existing across the base-collector junction promotes removal of charges from base-to-collector. To the extent that carrier transport resulting from removal of base charge can be explained in terms of diffusion mechanics alone, the collector current is directly proportional to the magnitude of the slope of injected charge profile. Thus, collector current increases are in one-to-one correspondence with increasing magnitude of charge profile slope.

Under saturated conditions, the collector current is fixed at the level defined by (2), despite the fact that photocurrent flow gives rise to continuing injection of charge into the base region. Since collector current, and therefore charge profile slope, is constant, the resultant charge distribution must mirror Figure (3b). The excess charge alluded to earlier is $Q_{BS}$, which materializes primarily from injection across a forward biased base-collector junction. In short, both junctions are

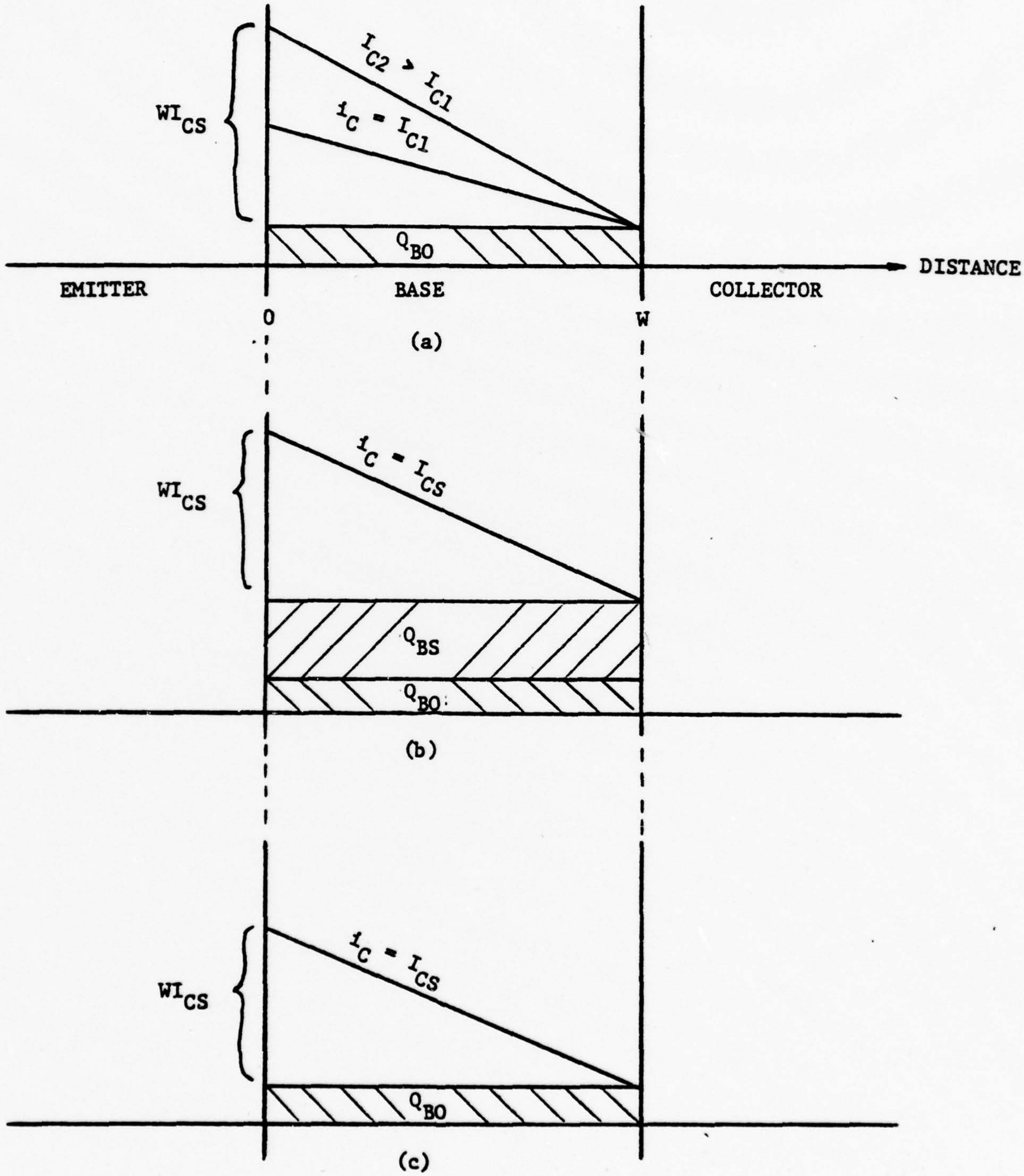



Figure (3). Charge Profiles In Base Region

(a) Normal Active Operation

(b) Saturated Conditions

(C) Threshold of Saturated-Normal Active Operation

forward biased in saturated regimes, and this condition is properly reflected in Figure (3b) by the fact that the charge distribution is not in equilibrium at either junction.

Upon termination of the radiation event, the collector current remains nominally constant for a time, $t_{SR}$. This situation can be visualized as spacially uniform removal of $Q_{BS}$, as suggested in Figure (3c). When $t_{SR}$ seconds have elapsed, the collector current commences its response to photocurrent pulse discontinuation, since further removal of charge mandates a decrease in profile slope magnitude. Note that at the instant when $Q_{BS} = 0$, the BJT is at the threshold of re-entering its linear active operating regime.

Figure (4) offers plots of the collector and base current responses to the photocurrent excitation defined in Figure (2). Observe that the base current decreases almost instantaneously at $t = 0$ to a level, $I_{BO}$, despite the fact that the collector current remains constant in the time interval, $0 < t < t_{SR}$. The magnitude of this change in base current is a function only of $I_{PP}$ and resistive loading in the base circuit, since the voltage across the strongly charged base-emitter junction cannot change instantaneously. To the extent that most of the excess charge, $Q_{BS}$, is swept primarily into either emitter or collector regions, the base current level of $I_{BO}$ is essentially a constant up to time $t_{SR}$. This statement reflects the tacit assumptions that (1) removal of $Q_{BS}$ does not perturb the charge stored as a result of forward injection from the emitter and (2) the base current component attributed to a forward biased base-collector junction is much smaller than the base current attributed solely to a forward-biased base-emitter junction.

Time $t_R$ is termed the "recovery time" of the BJT. It is conventionally defined as the time required for collector current decrease to within 5% of quiescent value, following a saturating event.

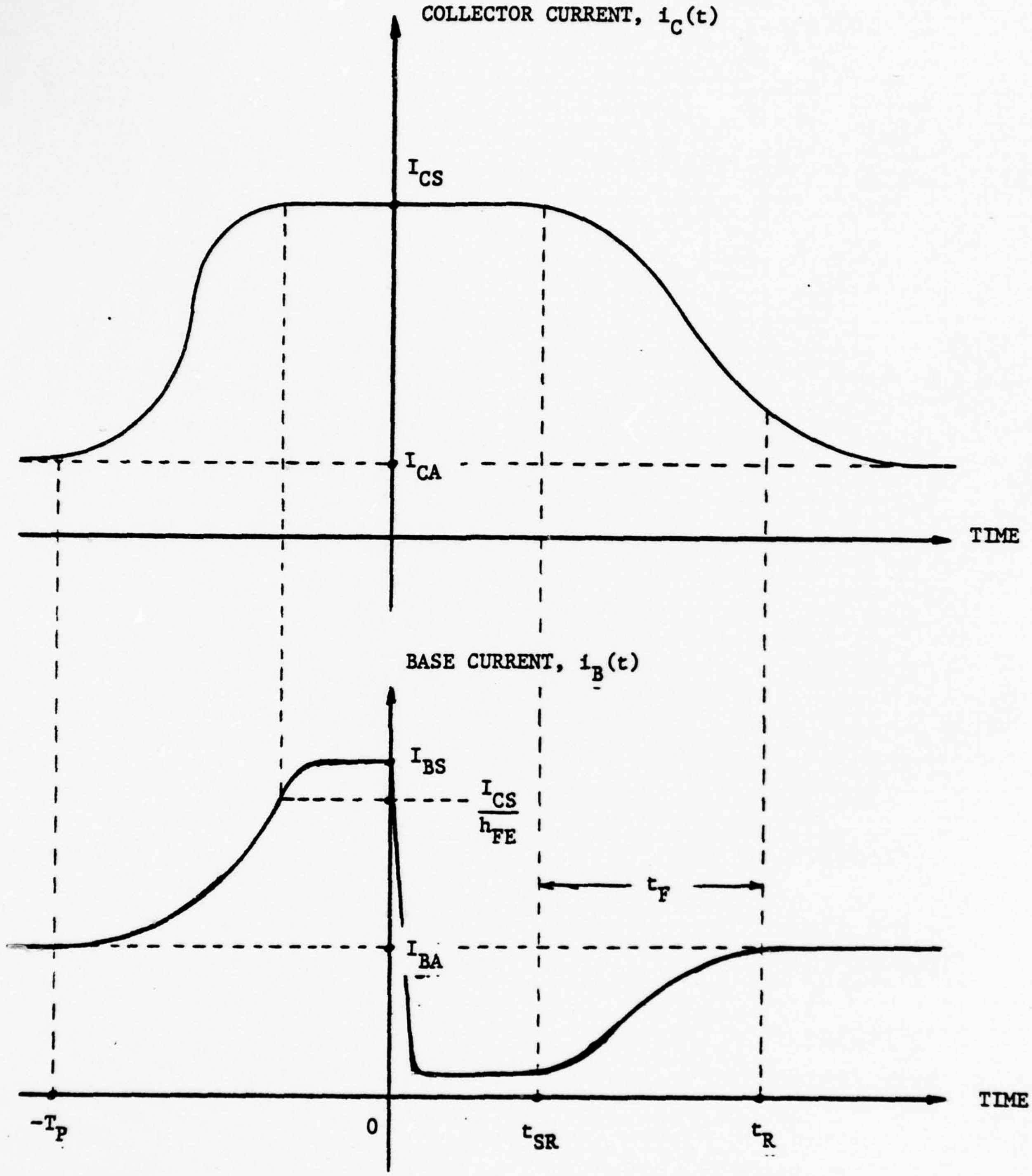



Figure (4). Collector And Base Current Responses To Photocurrent Excitation

(a) Collector Current Waveform

(b) Base Current Waveform

## 3.0 STORAGE TIME ANALYSIS

The low injection static equations which characterize BJT performance in all operating regimes are

$$I_E = I_S\left[\varepsilon^{V_E'/V_T} - 1\right] - I_S\left[\varepsilon^{V_C'/V_T} - 1\right] + \frac{I_S}{h_{FE}}\left[\varepsilon^{V_E'/V_T} - 1\right] \tag{3}$$

$$I_C = I_S\left[\varepsilon^{V_E'/V_T} - 1\right] - I_S\left[\varepsilon^{V_C'/V_T} - 1\right] - \frac{I_S}{h_{FR}}\left[\varepsilon^{V_C'/V_T} - 1\right], \tag{4}$$

where $V_E'$ and $V_C'$ are intrinsic voltages across base-emitter and base-collector junctions, respectively, $V_T$ is the voltage equivalent of absolute junction temperature (25.9mV at 300°K), and $I_S$ is termed a reference transport current. The static values of emitter current $I_E$ and collector current $I_C$ flow in the polarity directions defined in Figure (1), and voltages $V_E'$ and $V_C'$ are positive when the respective junctions are forward biased. Finally, parameter $h_{FE}$ is the forward gain exploited in (1), while $h_{FR}$ is the static reverse current transfer ratio; i.e., $h_{FR}$ is the gain that materializes if the roles of emitter and collector are interchanged.

An inspection of (3) and (4) readily indicates that both emitter and collector currents are superpositions of the effects of charge injection across base-emitter and base-collector junctions. Since the terms involving $V_E'$ are dominant for forward or linear active modes of operation, while the terms in $V_C'$ predominate under inverted operational circumstances, it is reasonable to decompose $I_E$ and $I_C$ into forward and inverse current components. Accordingly, let

$$I_E \triangleq I_{EF} - I_{EI} \tag{5}$$

$$I_C \triangleq I_{CF} - I_{CI}, \tag{6}$$

where

$$I_{EF} = \frac{I_S}{\alpha_F} (\epsilon^{V_E'/V_T} - 1), \tag{7}$$

$$I_{EI} = I_S (\epsilon^{V_C'/V_T} -1), \tag{8}$$

$$I_{CF} = \alpha_F I_{EF}, \tag{9}$$

$$I_{CI} = I_{EI}/\alpha_R. \tag{10}$$

In (7) through (10),

$$\alpha_F = \frac{h_{FE}}{h_{FE} + 1} \tag{11}$$

$$\alpha_R = \frac{h_{FR}}{h_{FR} + 1} \quad . \tag{12}$$

The decomposition of (3) and (4) into the form of (5) and (6) is significant in the sense that the constituents of the BJT current can be identified in terms of the charge storage components which materialize in the base due to injection across either junction. In particular, if $Q_{BS}$ in Figure (3) can be attributed solely to charges which traverse a forward-biased ($V_C' > 0$) base-collector junction, both $I_{EI}$ and $I_{CI}$ are non-zero only if the time rate of change of $Q_{BS}$ is non-zero. It follows that upon termination of the photocurrent pulse, a solution for radiation storage time, $t_{SR}$, embodies an investigation of the time at which $I_{EI}$ and $I_{CI}$ vanish.

Although the foregoing solution tact is meaningful, (5) through (10) are incapable of delivering time-domain response information unless they are modified to account for charge dynamics in the base. These dynamics are typically modeled by currents flowing across nonlinear junction capacitances which charge or discharge upon application or removal of the photocurrent pulse. A first order account of dynamical charge effects is accomplished by replacing constants $\alpha_F$ and $\alpha_R$ in (11) and (12) by the respective complex frequency transforms,

$$\alpha_F(s) = \frac{\alpha_{FO}}{1 + s/\omega_F} \tag{13}$$

$$\alpha_R(s) = \frac{\alpha_{RO}}{1 + s/\omega_F} \quad . \tag{14}$$

In the above relationships, $\omega_F$ is defined as the forward gain-bandwidth product, while $\omega_R$ is the inverted analog of $\omega_F$. Specifically, $\omega_F$ is the radial gain bandwidth product of forward common-emitter current gain, and $\omega_R$ is the radial gain bandwidth product of inverse common-emitter current gain.

In the time interval, $0 \leq t \leq t_{SR}$, it may be argued that the inverse components of emitter and collector currents are expressible in the form,

$$i_{EI}(t) = i_{EI}(0) + \Delta i_{EI}(t) \tag{15}$$

$$i_{CI}(t) = i_{CI}(0) + \Delta i_{CI}(t) \; . \tag{16}$$

In (15) and (16), $i_{EI}(0)$ and $i_{CI}(0)$ are steady-state inverse currents which exist immediately prior to termination of photocurrent excitation. On the other hand, $\Delta i_{EI}(t)$ and $\Delta i_{CI}(t)$ are changes incurred in the inverse emitter and collector currents during the interval of radiation storage time. Clearly, radiation storage time, $t_{SR}$, can be defined implicitly as the largest of the two times, $t_{SRE}$ and $t_{SRC}$, such that

$$\Delta i_{EI}(t_{SRE}) = i_{EI}(0). \tag{17}$$

$$\Delta i_{CI}(t_{SRC}) = i_{CI}(0). \tag{18}$$

It is necessary to stipulate

$$t_{SR} = \mathrm{MAX}(t_{SRE}, t_{SRC}), \tag{19}$$

since the transistor re-enters its active operational region only when all inverse current flow ceases.

From (5) through (10), it is easily shown that

$$I_{EI}(s) = \left[\frac{\alpha_R(s)}{1 - \alpha_F(s)\alpha_R(s)}\right]\left[\alpha_F(s)I_E(s) - I_C(s)\right] \tag{20}$$

$$I_{CI}(s) = \left[\frac{\alpha_F(s)I_E(s) - I_C(s)}{1 - \alpha_F(s)\alpha_R(s)}\right] \tag{21}$$

whence, by (13) and (14)

$$i_{EI}(0) \equiv I_{EI} = \left(\frac{\alpha_{RO}}{1 - \alpha_{FO}\alpha_{RO}}\right)\left(\alpha_{FO}I_E - I_C\right) \tag{22}$$

$$i_{CI}(0) \equiv I_{CI} = \frac{\alpha_{FO}I_E - I_C}{1 - \alpha_{FO}\alpha_{RO}} \; . \tag{23}$$

In (22) and (23), it is to be understood that $I_E$ and $I_C$ represent the steady state irradiated values of emitter and collector current, respectively.

Since the collector current is nominally constant for $0 \leq t \leq t_{SR}$, the transforms of the incurred changes in inverse currents are, from (20) and (21),

$$\Delta I_{EI}(s) = \left[\frac{\alpha_F(s)\alpha_R(s)}{1 - \alpha_F(s)\alpha_R(s)}\right] \Delta I_E(s) \tag{24}$$

$$\Delta I_{CI}(s) = \Delta I_{EI}(s)/\alpha_R(s). \tag{25}$$

From Figures (1) and (5), the net change in emitter current during the storage time interval is

$$I_E(s) = \frac{1}{s}\left[\left(I_{BO} + I_{CS}\right) - \left(I_{BS} + I_{CS}\right)\right] = -\frac{1}{s}\; I_{BS} - \left(I_{BS} - I_{BO}\right)\Big] \; , \tag{26}$$

where $I_{BO}$ is the nominal base current flowing in the time interval, $0 < t < t_{SR}$. By virtue of the charge storage arguments presented earlier,

$$I_{BO} = I_{BS} - \left(\frac{R_{BB}}{R_{BB} + R_B}\right) I_{PP}, \tag{27}$$

where $R_B$ is the ohmic resistance of the active base region. Substitution of (13), (14), and (26) into (24) leads to the second-order transform,

$$\Delta I_{EI}(s) = - \frac{\alpha_{FO}\alpha_{RO}\omega_F\omega_R \; (I_{BS} - I_{BO})/s}{s^2 + (\omega_F + \omega_R)s + (1 - \alpha_{FO}\alpha_{RO})\omega_F\omega_R} . \tag{28}$$

Assuming $\omega_F >> \omega_R$ (1), (28) reduces to

$$\Delta I_{EI}(s) \simeq - \frac{\alpha_{FO}\alpha_{RO}\omega_R \; (I_{BS} - I_{BO})}{s \; (s + s_o)}, \tag{29}$$

where

$$s_o \triangleq \frac{(1 - \alpha_{FO}\alpha_{RO})\omega_R\omega_F}{\omega_R + \omega_F} \simeq (1 - \alpha_{FO}\alpha_{RO})\omega_R. \tag{30}$$

The inverse transform of (29) is

$$\Delta i_{EI}(t) = - \left(\frac{\alpha_{FO}\alpha_{RO}}{1 - \alpha_{FO}\alpha_{RO}}\right) (I_{BS} - I_{BO}) \; (1 - \epsilon^{-s_o t}), \tag{31}$$

for $0 \leq t \leq t_{SRE}$. An analogous tact produces

$$\Delta i_{CI}(t) = - \left(\frac{\alpha_{FO}}{1 - \alpha_{FO}\alpha_{RO}}\right) (I_{BS} - I_{BO}) (1 - \alpha_{FO}\alpha_{RO} \; \epsilon^{-s_o t}) \tag{32}$$

in the interval, $0 \leq t \leq t_{SRC}$, for the change in the inverse component of collector current.

---

(1) The inverse bandwidth is much smaller than the forward bandwidth owing to the reduced transport efficiency incurred as a result of charge injection from a lightly doped collector and charge collection by a heavily doped emitter.

An expression for $t_{SRE}$ evolves straight-forwardly if (17), (22), and (31) are combined. A satisfying form for this expression rests on the observation that in (22),

$$\alpha_{FO}I_E - I_C = \alpha_{FO}(I_{CS} + I_{BS}) - I_{CS} = \alpha_{FO}(I_{BS} - I_{CS}/h_{FE}).$$

In particular, it can be shown that

$$t_{SRE} = \frac{1}{S_o} \text{Ln}\left(\frac{1}{1 - N_o}\right) , \tag{33}$$

with

$$N_o \triangleq \frac{I_{BS} - I_{CS}/h_{FE}}{I_{BS} - I_{BO}} . \tag{34}$$

Similarly,

$$t_{SRC} = \frac{1}{S_o} \text{Ln}\left(\frac{\alpha_{FO}\alpha_{RO}}{1 - N_o}\right). \tag{35}$$

Since $\alpha_{FO}\alpha_{RO}$ is less than unity, $t_{SRE} > t_{SRC}$ and thus,

$$t_{SR} \cong t_{SRE}. \tag{36}$$

It might be noted in passing that the inequality, $t_{SRE} > t_{SRC}$ is a reasonable result. This assertion follows from the fact that since inverse current flow reflects charge transport from collector-to-emitter, the time difference, $t_{SRE} - t_{SRC}$, represents delays associated with charge transport across the base layer of the BJT.

There is considerable engineering significance to the parameter, $N_o$, defined by (34). Observe that the ratio, $I_{CS}/h_{FE}$, is the minimum base current required for BJT saturation in the steady state. This is to say that a static base current of $I_{CS}/h_{FE}$ is commensurate with the onset of inverse injection across base-collector junction. A slightly larger base drive delivers $Q_{BS} > 0$, and the BJT is forced into saturation. It follows that since $I_{BS}$ is the actual steady state base current for the saturated BJT, $(I_{BS} - I_{CS}/h_{FE})$ in the numerator on the right hand side of (34) represents the excess base current commensurate with assurance

of a saturated condition. Recalling that $I_{BO}$ is the base current evidenced immediately after cessation of the photocurrent, $(I_{BS} - I_{BO})$ in (34) can be viewed as the driving current serving to effect recovery of the BJT. Since $I_{BO}$ must be smaller than $I_{CS}/h_{FE}$ if the BJT is indeed to recover, $N_o$ is always less than one. Accordingly, $N_o$ might be termed a "recovery" factor in the sense that it compares the base current needed for device recovery to the excess base current required to ensure device saturation. As is inferred by Figure (5), minimal radiation storage time is in one-to-one correspondence with small $N_o$. In turn, small $N_o$ demands a small $R_B/R_{BB}$ ratio, since from (3), (27), and (34),

$$N_o = \left(1 + \frac{R_B}{R_{BB}}\right)\left(1 - \frac{V_{BSAT}/R_{BB} + I_{CS}/h_{FE} - I_S}{I_{PP}}\right) . \tag{37}$$

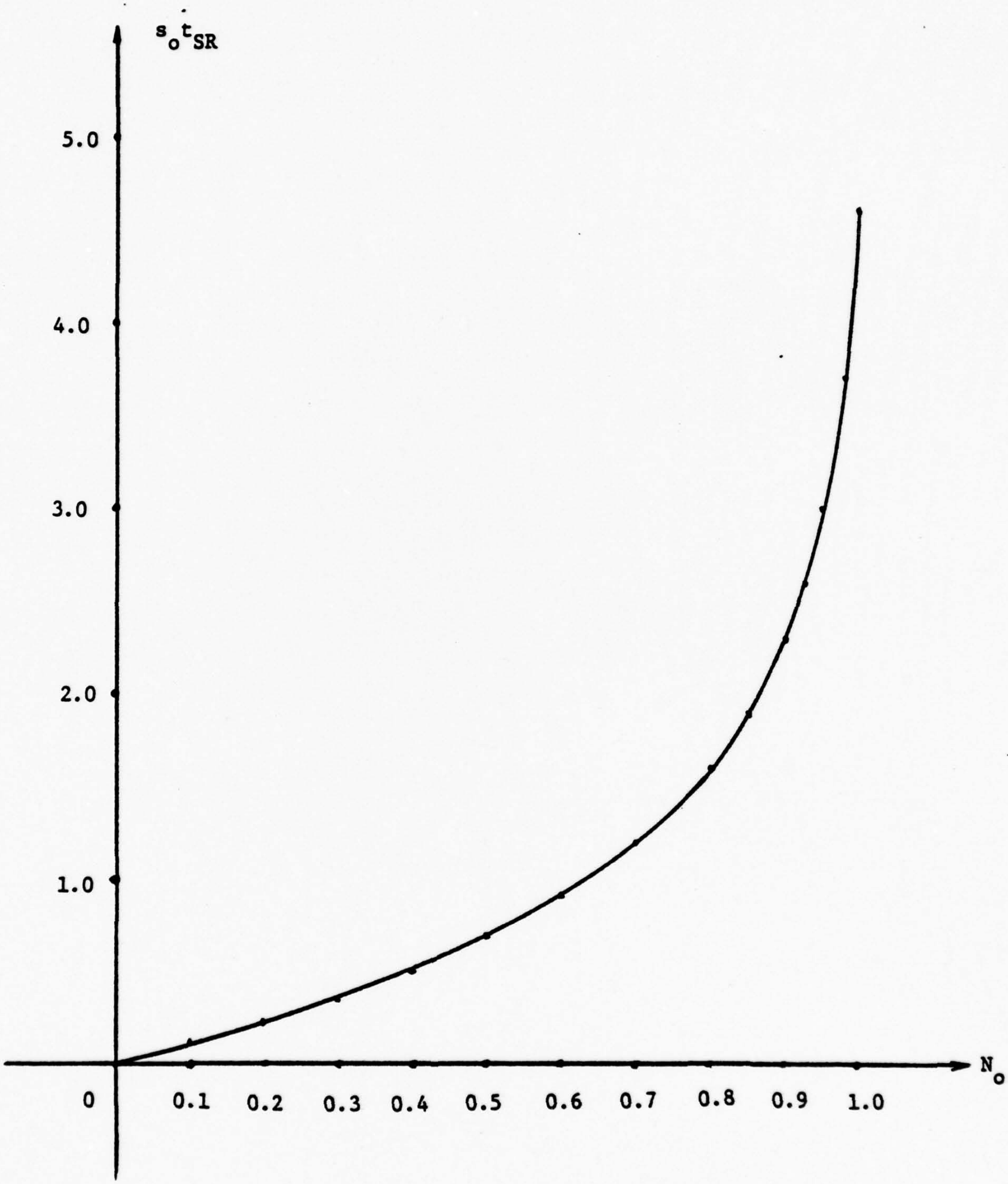



Figure (5). Normalized Radiation Storage Time As A Function of Recovery Factor, $N_o$

## 4.0 RECOVERY TIME

From Figure (4), the recovery time, $t_R$, is the superposition of radiation storage time, $t_{SR}$, and the so-called fall time, $t_F$. In the fall-time interval, $t_{SR} < t < t_R$, the BJT is in its linear active region of operation and if pole dominance can be assumed, the collector current waveform may be approximated by a single time constant expression of the form,

$$i_C(t) = \left[ I_{CA} - (I_{CA} - I_{CS})\varepsilon^{-(t - t_{SR})/T_P} \right] \mu(t - t_{SR}). \tag{38}$$

In (38), $\mu(t)$ is the unit step function, and $T_P$ is the first time moment of the small-signal model used to simulate the collector current response. Taking $i_C(t_R) = 1.05I_{CA}$, (38) delivers,

$$t_F = T_P \left[ 3.0 + \mathrm{Ln}\left( \frac{I_{CS}}{I_{CA}} - 1 \right) \right] . \tag{39}$$

Figure (6) depicts the small-signal model alluded to in the preceeding paragraph [1]. In this model, $r_\pi$ is the diffusion resistance of the base-emitter junction, $r_o$ is the incremental output resistance, $C_\mu$ is the transition capacitance of the reverse-biased base-collector junction, $C_\pi$ is the diffusion capacity of the base-emitter junction, and $\beta_o$ is the small-signal common-emitter current gain of the BJT. The first time moment, which equates to the inverse of the dominant pole frequency, is the sum of the time constants individually attributed to $C_\pi$ and to $C_\mu$, respectively. By straight-forward circuit analysis,

$$T_P = R_i \left[ C_\pi + \left( 1 + \frac{\beta_o R_L}{r_\pi} \right) C_\mu \right] + R_L C_\mu , \tag{40}$$

where

$$R_i = \frac{r_\pi (R_B + R_{BB})}{r_\pi + R_B + R_{BB}} , \tag{41}$$

$$R_L = \frac{r_o R_C}{r_o + R_C} . \tag{42}$$

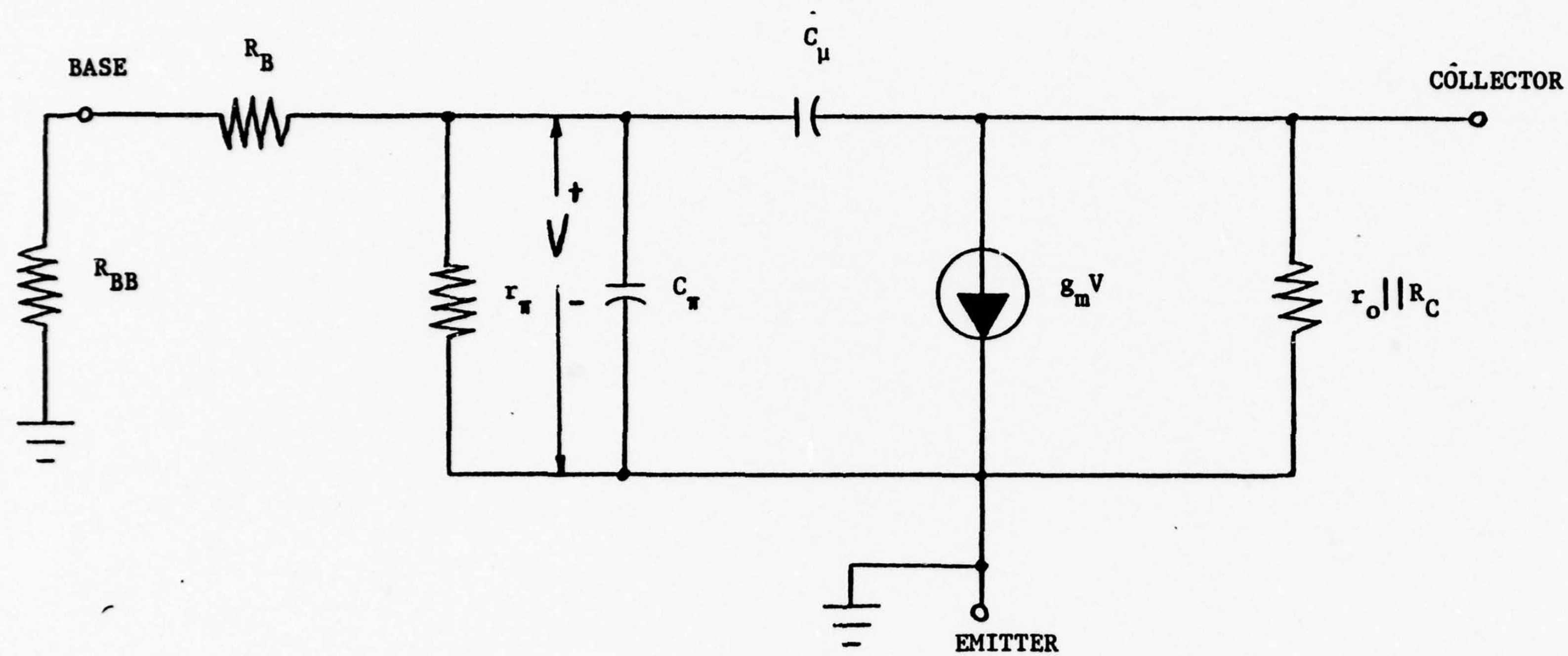



Figure (6). Small-Signal Bipolar Transistor Model Used in the Computation of Fall Time

Assuming $\beta_o >> r_\pi/R_L$, (40) can be cast into the form

$$T_P \approx \left(\frac{R_B + R_{BB}}{R_B + R_{BB} + r_\pi}\right)\left(\frac{1}{\omega_F} + R_L C_\mu\right)\beta_o, \tag{43}$$

where

$$\omega_F = \frac{\beta_o}{r_\pi (C_\pi + C_\mu)} \tag{44}$$

is the short-circuit common-emitter gain-bandwidth product, as defined in conjunction with (13).

Care must be exercised in the utilization of (43) and (44), since these results derive from a linearized model which may inappropriately simulate the effects of large collector current excursions. In particular, the model does not incorporate the variations in small-signal parameters incurred by large changes in device currents and voltages. Accordingly, one can rationalize the tact of conservatively estimating $t_F$ by choosing a worst case maximum value of $T_P$. From (43) and its companion equations, it is clear that a realistic maximum value for $T_P$ is

$$T_{PMAX} = \beta_{oMAX}\left[\frac{1}{\omega_{FMIN}} + R_C C_{ob}\right], \tag{45}$$

with the understanding that $\beta_{oMAX}$ and $\omega_{FMIN}$ are extrema pertinent to the current excursion, $I_{CS}$-to-$I_{CA}$, and the corresponding collector-emitter voltage variation, $V_{CSAT}$-to-$(V_{CC} - I_{CA}R_C)$. Furthermore, $C_{ob}$, the common-base output capacitance for zero collector-base bias, is a commonly specified device parameter which exceeds, but closely approximates, small-signal capacitance $C_\mu$.

## 5.0 EXAMPLE CALCULATION

Assume that the circuit of Figure (1) has $R_C$ = 500 ohms, $R_{BB}$ = 5,000 ohms, $V_{CC}$ = 5 volts, and $I_S$ = 200 micro-amperes. Assume further that the BJT is characterized by the following parameters:

$h_{FE}$ = 50;

$f_{TMIN}$ = 80MHz

$f_R$ = 3MHz (inverse gain-bandwidth);

$C_{ob}$ = 2.5pF;

$\beta_{oMAX}$ = 150;

$R_B$ = 800 ohms

$h_{FR}$ = 0.4;

$V_{BSAT}$ = 2.3 volts (includes ohmic drop in $R_B$);

$V_{CSAT}$ = 0.55 volts.

Finally, let the BJT be exposed to a gamma dose-rate event which gives rise to a photocurrent pulse amplitude of 2 milli-amperes.

From (2), the collector saturation current is

$$I_{CS} = \frac{5 - 0.55}{500} - (2)(10^{-3}) = 6.9\text{mA},$$

while (3) yields for saturated base current,

$$I_{BS} = (200)(10^{-6}) + (2)(10^{-3}) - \frac{2.3}{5000} = 1.74\text{mA}.$$

Taking $V_{BE}$ = 0.78 volt for linear active operation, Figure (1) shows that the pre-irradiated value of base current is

$$I_{BA} = I_S - \frac{V_{BE}}{R_{BB}} = (200)(10^{-6}) - \frac{0.78}{5000} = 44\mu A;$$

hence, from (1), the corresponding collector current is

$$I_{CA} = (50)(44) = 2.2mA.$$

Finally, (27) produces

$$I_{BO} = (1.74)(10^{-3}) - (\frac{5000}{5800})(2)(10^{-3}) = 15.9\mu A.$$

Using (11) and (12),

$$\alpha_{FO} = \frac{50}{51} = 0.98$$

and

$$\alpha_{RO} = \frac{0.4}{1.4} = 0.29.$$

Then by (30),

$$s_o = \left[1 - (0.98)(0.29)\right]\left[2\pi(3)(10^6)\right] = 13.5MRPS.$$

Equation (34) gives for the the recovery factor,

$$N_o = \frac{(1.74)(10^{-3}) - (6.9)(10^{-3})/50}{(1.74)(10^{-3}) - (15.9)(10^{-6})} = 0.929,$$

whence (33) and (36) deliver

$$t_{SR} = \frac{1}{(13.5)(10^6)} \quad Ln\left[\frac{1}{1 - 0.929}\right] = 196nsec$$

for the estimated radiation storage time.

Using (21),

$$T_{PMAX} = 150 \left[ \frac{1}{2\pi (80)(10^6)} + (500)(2.5)(10^{-12}) \right] = 486\text{nsec.}$$

Then from (39),

$$t_{FMAX} = (486)(10^{-9}) \left[ 3.0 + \text{Ln}\, \frac{6.9}{2.2} - 1 \right] = 1.83\mu\text{sec.}$$

Thus, the estimated worst case BJT recovery time is

$$t_{RMAX} = t_{FMAX} + t_{SR} = 2.0\mu\text{sec.}$$

Observe in the foregoing example that the storage time is in the order of 10% of the maximum recovery time. This result generally reflects situations actually encountered in realistic radiation test environments. Accordingly, it follows that BJT recovery time is largely determined by time moment parameter $T_{PMAX}$. In turn, $T_{PMAX}$ is minimal for devices which exude low collector-base capacitance, large gain bnadwidth product, and low small-signal current gain.

## 6.0 CONCLUSIONS

An analysis of the radiation recovery transient in a bipolar junction transistor subjected to a saturating dose rate event has been developed. The analysis, which is supplemented by exemplifying calculations of recovery time, reveals device parameters and performance attributes that must be critically scrutinized if recovery time is to be constrained to a minimum. Although the general nature of sensitive device parameters is properly uncovered, it is crucial that approximations invoked during the course of analysis be understood, particularly if the primary objective of utilizing the analysis in a given application is realistic absolute estimation of recovery time.

Undoubtedly, the most significant assumption is that BJT currents flow by diffusion mechanisms alone. In simplified terminology, it has been presumed that (1) the injected charge profile in the base is linearly graded, (2) the collector current is proportional to the magnitude of profile gradient, and (3) the excess stored charge is removed prior to removal of charge accumulated from forward injection across the base-emitter junction. In reality, drift components of BJT currents are at least comparable to, if not larger than, the diffusion components in saturated devices. These drift components loom increasingly more important if the actual base current is allowed to increase significantly over the minimum base current ($I_{CS}/h_{FE}$) commensurate with the threshold of saturation.

Aside from compromising the foregoing three presumptions, the immediate effect of non-negligible current transport via high-field drift mechanisms is high-current, low-voltage degradation in the gain-bandwidth product, $\omega_F$[2]. The maximum amount of degradation is proportional to the square of the ratio of epitaxial layer length-to-neutral base width. Depending on the type of BJT addressed, the extent of this degradation can be in the range of 15-to-20. Similar attenuations are evidenced with respect to both the static and small-signal current gains, although the factor by which these gains degrade is not as severe as the degradations quoted for gain-bandwidth product. The upshot of the matter is that if manufacturer's gain-bandwidth product and gain specifications

are used to compute $T_{PMAX}$, it is conceivable that the estimated maximum recovery time might be low by factors in the range of 5-to-10, since device specifications are invariably applicable to operational regions other than high-injection regimes.

It must also be remembered that (38) and (39) presume device linearity and pole dominance for $t_{SR} < t < t_R$. The effects of inherent device nonlinearities are especially pronounced if the saturated-to-quiescent collector current ratio, $I_{CS}/I_{CA}$, is larger than four or five. Ringing in the collector and base current responses is indicative of either circuit nonlinearity or a non-dominant pole population. Indeed, if non-linearity is particularly severe, the analytical concept of a pole cannot be exploited in the computation of fall time $t_F$. It can be envisaged that the impropriety of either linearity or pole dominance is conducive to recovery time estimates that are low by 20%-to-40%.

In summary, it is suggested that the foregoing equations are useful in ascertaining device characteristics which strongly influence the radiation recovery response of a BJT. They are also useful when applied to the problem of bracketing a realistic estimate of maximum recovery time. The lowest anticipated maximum recovery time derives from direct employment of manufacturer's nominal specifications for key device parameters. The largest estimate for maximal recovery time is obtained by allowing gain and gain-bandwidth product to degrade in accordance with specified, or estimated high-injection device performance characteristics.

## 7.0 REFERENCES

1. J. Choma, Jr., "Process-Oriented, High Injection Circuit Models for Integrated Bipolar Junction Transistors," Office of Naval Research, Report No. N00014-75-C-1177, November 1976.

2. J. Choma, Jr., "A Process-Oriented Model for the Simulation of Base Pushout in Integrated Bipolar Devices," IEEE Transactions on Electron Devices, Vol. ED-22, pages 1079-1086, December 1975.

# APPENDIX E

## CIRCUIT MODEL FOR NEUTRON-INDUCED PERFORMANCE DEGRADATION IN BIPOLAR JUNCTION TRANSISTORS

CIRCUIT MODEL FOR NEUTRON-INDUCED

PERFORMANCE DEGRADATION IN BIPOLAR JUNCTION TRANSISTORS

J. Choma, Jr., Senior Member

IEEE

J. M. Oberholtzer

ABSTRACT:

This paper proposes the use of an existing large-signal circuits model to simulate bipolar transistor performance degradation induced by neutron irradiation. It is shown that only three radiation parameters are required to establish a model for neutron effects over the entire practical current and voltage ranges of bipolar transistor operation.

September, 1977

## 1.0 INTRODUCTION

The predominant effects of neutron displacement damage in silicon are an increase in carrier generation rate and a decrease in majority carrier concentration. In a bipolar junction transistor (BJT), these effects combine to produce current gain attenuation, degradation in gain-bandwidth product, enhanced base-collector leakage current, increased collector breakdown voltage, and increased collector saturation voltage [1]. Additionally, neutron displacement damage in a BJT may significantly perturb the nominal thermal characteristics of a bipolar circuit. Depending on circuit configuration, the nominal thermal behavior can either be aggravated or improved by neutron bombardment [2]-[3].

Traditionally, the performance of bipolar circuits immersed in a neutron environment is simulated by exploiting various damage constants which are enumerated from experimental device characterizations. In particular, gain, leakage current, and gain-bandwidth product are measured prior to and immediately following controlled neutron irradiation of a given bipolar device. This data is used to extrapolate simple relationships between pre-irradiated and irradiated values of various device parameters. An example of such a relationship is the Messenger-Spratt equation [4],

$$\frac{1}{\beta_\phi} = \frac{1}{\beta_o} + K_\phi \tau_{FO} \Phi, \tag{1}$$

where $\beta_\phi$ is the irradiated value of static short-circuit current transfer ratio, $\beta_o$, $\tau_{FO}$ is the transit time of minority carriers across the neutral base, $\Phi$ is neutron fluence, and $K_\phi$ is the pertinent damage constant. Other device performance indices, such as gain-bandwidth product, breakdown voltage, and leakage current, are related to device neutron fluence exposure by expressions whose forms are analogous to (1).

Although neutron-induced damage assessment equations are useful both for simulating the dependence of irradiated electrical parameters on their pre-irradiated counterparts and for establishing a basis of neutron hardness screening, at least two fundamental objections can be raised if these equations are used exclusively in evaluating bipolar response to neutron irradiation.

First, the damage constant methodology can only simulate measured results. It cannot be applied to the problem of predicting the radiation response of bipolar transistors, because the damage constants are empirical performance barometers. These constants are not well-defined in terms of intrinsic physical or geometrical device properties but instead, they derive purely from experimental data.

A second shortcoming is that most of the damage constants invoked in a neutron radiation response exercise are sensitive functions of device injection level. For example, $K_\phi$ in (1) varies with the voltage and current at which gain $\beta_o$ is measured. The upshot of the matter is that most damage assessment equations are applicable only to the injection regime in which they are formulated. Attempts made to invoke these same equations to damage assessment at significantly lower or higher injection levels generally result in substantial analytical errors. It follows that the methodology in question conveys little, if any, understanding of the sensitivity of neutron radiation response with respect to the possibly wide injection range which a bipolar device encounters in a prescribed circuit application.

This paper presents a new bipolar neutron damage model which is uniformly applicable to the low-through-high injection range of BJT operation. The model is an extension of an existing circuits model which is capable of predicting large-signal transient responses to forcing inputs that can drive the transistor from low-to-high injection regimes. In addition to the model parameters pertinent to simulation and prediction of traditional electrical responses, only three additional parameters are required for an evaluation of the effects of neutron radiation. These parameters are independent of voltage and current and moreover, they can be related to damage constants which have been enumerated from a damage assessment appropriate to mid-injection operational regimes.

## 2.0 FUNDAMENTAL TRANSISTOR MODEL

The bipolar transistor circuit model diagrammed in Figure (1) is proposed as the foundation for neutron radiation response studies.[(1)] The model possesses all of the attributes of the classical Ebers-Moll [5] and Gummel-Poon [6] topologies and in addition, it provides the following simulation capabilities.

(1). The effects of base-collector depletion layer width modulations arising out of collector junction voltage changes are incorporated. This phenomenon, known as the Early Effect [7], gives rise to current gain dependence on collector voltage. Analogously, an account is made of Inverse Early Effect, which produces inverse beta dependence on base-emitter voltage.

(2). Low-injection forward current gain attenuation due to non-ideal diode currents flowing across the base-emitter junction is replicated by the model. In Figure (1), the lumped equivalent to the non-ideal base-emitter diode current is

$$I_{BEN} = I_{ER}(\varepsilon^{V_E'/N_E V_{TE}} -1), \qquad (2)$$

where $V_{TE}$ is junction thermal voltage, and $I_{ER}$ and $N_E$ relate implicitly to emitter efficiency, degree of emitter sidewall injection, and the recombination velocity at the base-emitter interface. Parameter $N_E$ is always greater than or equal to unity. The diode current, $I_{BCN}$, mathematically parallels the form of (2) and allows for low-level inverse current gain attenuation for transistors operated in inverted or saturated modes.

---

(1) The model, which was developed by the author at the University of Pennsylvania, is embedded in the ISPICE computer-aided design program and is available on a timeshare network marketed by National CSS, Inc., Norwalk, Connecticut.

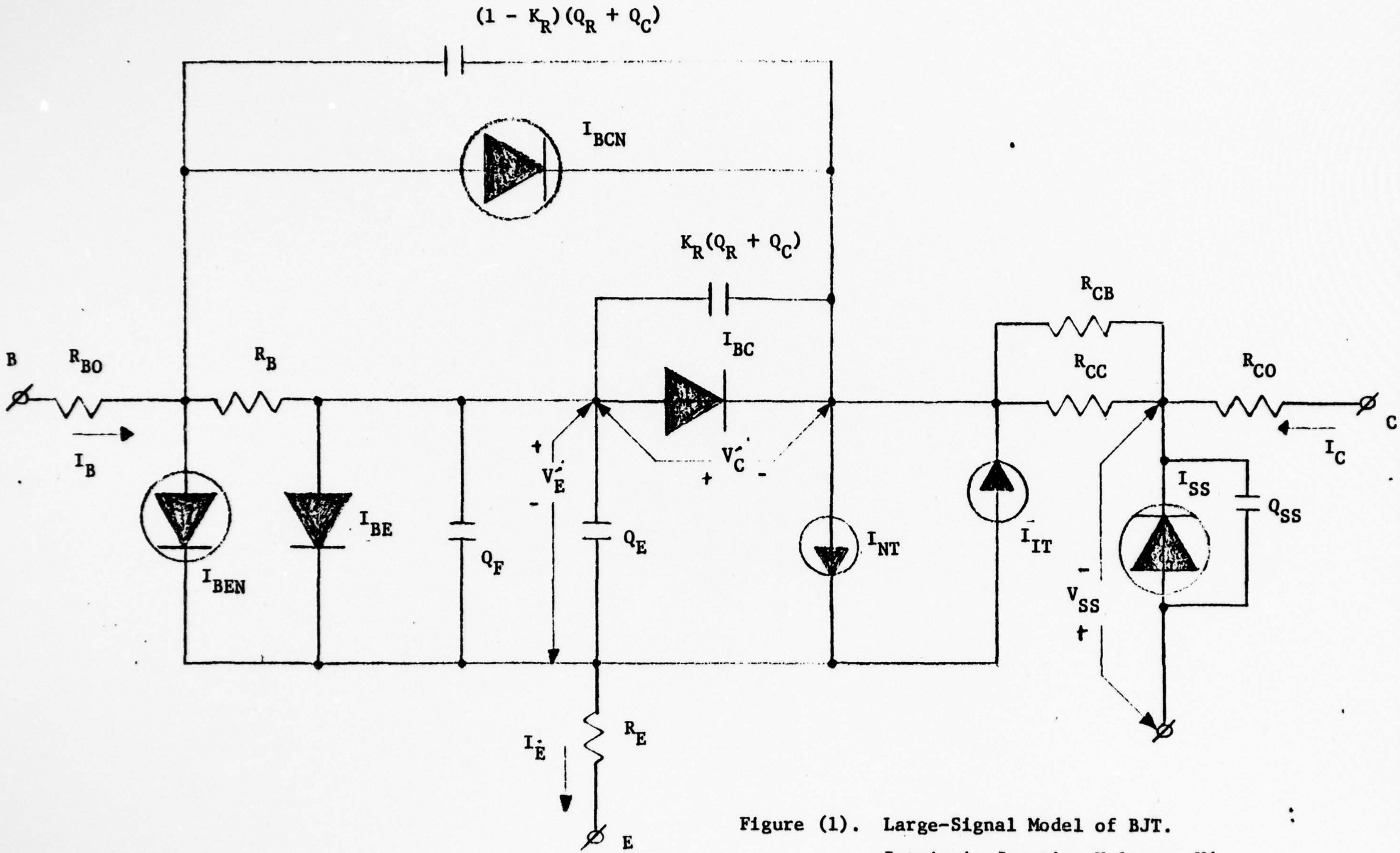



Figure (1). Large-Signal Model of BJT. Intrinsic Junction Voltages $V'_E$ and $V'_C$ are positive when they serve as forward biasing voltages.

(3). High-injection forward current gain degradation caused by conductivity modulation in both the base and quasi-saturated collector regions is incorporated in the model of Figure (1). The element germane to this simulation capability is

$$I_{NT} = \left(\frac{Q_{BO}}{Q_B}\right) I_S(\varepsilon^{V_E'/V_{TE}} - 1), \tag{3}$$

where $Q_B$, the net majority charge in the effective base, has a value of $Q_{BO}$ under zero bias ($V_E' = V_C' = 0$) conditions. The charge function, $Q_B$, which is the superposition of charge $Q_E$ stored in the base-emitter transition layer, charge $Q_C$ stored in the base-collector depletion region, and the charges ($Q_F$ and $Q_R$) required to preserve space-charge neutrality in the face of charge injection across either junction, is given by

$$\frac{Q_B}{Q_{BO}} = (1 + \lambda_E) + \frac{\tau_F I_S(\varepsilon^{V_E'/V_{TE}} - 1)}{Q_B} + \frac{\tau_R I_S(\varepsilon^{V_C'/V_{TC}} - 1)}{Q_B} . \tag{4}$$

In (4),

$$\lambda_E = \frac{V_E'}{V_{ER}} + \frac{V_C'}{V_{CR}} , \tag{5}$$

where $V_{ER}$ and $V_{CR}$ are inverse and forward Early effect parameters, and $\tau_F$ ($\tau_R$) is the forward (inverse) transit time of minority carriers in the field-neutral base. Because of base pushout phenomena, these transit times vary with device current and voltage [8]. Parameter $I_S$ in (3) and (4) is directly proportional to the product of intrinsic carrier concentration and carrier diffusivity in the base, and it relates inversely to the total majority charge in the base region.

(4). High-injection gain-bandwidth product ($f_T$) degradation caused by base pushout and conductivity modulation in the collector layer is a model feature. The model also addresses the related nonlinearity in effective collector resistance, ($R_{CC} + R_{CO}$).

(5). The effects of static emitter crowding on the effective base resistance, $(R_{BO} + R_{BB})$, are embodied in the model. Excess phase and both static and dynamic conduction across the collector substrate interface are also included.

(6). A first order approximation of the distributed effects of high-frequency excitation is introduced by way of the semi-empirical parameter, $K_R$ $(K_R \leq 1)$.

## 3.0 LOW-INJECTION CURRENT GAIN DEGRADATION

Under static forward bias operating conditions, all charge functions vanish, the substrate diode current, $I_{SS}$, is very nearly zero, and currents $I_{BCN}$, $I_{BC}$, and $I_{IT}$, which are exponential functions of the intrinsic base-collector junction voltage, are essentially zero. Accordingly, Figure (1) verifies that base current $I_B$ is given by

$$I_B = I_{BE} + I_{BEN}, \tag{6}$$

where $I_{BEN}$ is defined by (2) and

$$I_{BE} = \frac{I_S}{\beta_o} [\varepsilon^{V_E'/V_{TE}} - 1]. \tag{7}$$

In (7), $\beta_o$ is the maximum value of the static transfer ratio,

$$h_{FE} = \frac{I_C}{I_B}, \tag{8}$$

under the special condition of zero bias $(V_C' = 0)$ across base-collector junction.

Returning to Figure (1), it is clear that under the conditions stipulated above, the collector current, $I_C$, is identical to the current, $I_{NT}$. From (3) and (4) it can be shown that

$$I_C = \frac{I_S(\varepsilon^{V_E'/V_{TE}} - 1)}{\left(\frac{1+\lambda_E}{2}\right) + \left\{\left(\frac{1+\lambda_E}{2}\right)^2 + Q_{FN}(\varepsilon^{V_E'/V_{TE}} - 1) + Q_{RN}(\varepsilon^{V_C'/V_{TC}} - 1)\right\}^{1/2}}, \quad (9)$$

where

$$Q_{FN} \triangleq \frac{\tau_F I_S}{Q_{BO}} \quad (10)$$

$$Q_{RN} \triangleq \frac{\tau_R I_S}{Q_{BO}} . \quad (11)$$

The term involving $Q_{RN}$ in (9) is essentially zero, provided that the BJT is operated in its linear active domain. Moreover, for low-to-moderate injection levels, the term containing $Q_{FN}$ is negligible, so that (9) collapses to

$$I_C \simeq \left(\frac{I_S}{1+\lambda_E}\right) \varepsilon^{V_E'/V_{TE}}. \quad (12)$$

In (12), it is assumed that the exponential term is much larger than unity. If this same reasonable assumption is invoked on (2), (8) can be shown to deliver

$$h_{FE} \simeq \frac{\beta_o/(1+\lambda_E)}{1 + \mathrm{EXP}\left[\left(\frac{N_E - 1}{N_E}\right)\left(\frac{V_K - V_E'}{V_{TE}}\right)\right]}, \quad (13)$$

with

$$V_K \triangleq \left(\frac{N_E}{N_E - 1}\right) V_{TE} \mathrm{Ln}\left(\frac{\beta_o I_{ER}}{I_S}\right). \quad (14)$$

Figure (2) portrays the dependence of $h_{FE}$ and $V_E'$, and hence the dependence of $h_{FE}$ on the natural logarithm of collector current $I_C$. Recalling (5), the effect of parameter $\lambda_E$, as depicted in the figure, is to simulate the sensitivity of current gain with respect to the reverse biasing voltage applied at the collector. Observe then that for increasing $V_E'$, $h_{FE}$ correctly approaches a constant at fixed collector junction voltage, provided that the contribution of $V_E'$ to $\lambda_E$ is insignificant in comparison to the contribution of $V_C'$. For decreasing forward bias, $h_{FE}$ attenuates in such a way that at $V_E' = V_K$, $h_{FE}$ is one-half of the current gain at moderate current levels. Notice that $V_K$ is dependent on both $I_{ER}$ and $N_E$, which implicitly relate to the characteristics of the base-emitter interface. Finally, $N_E$ fixes the slope of the gain curve at $V_E' = V_K$. If $N_E = 1$, which infers only idealized diode current flow across the base-emitter junction, $h_{FE}$ is constant over the addressed range of $V_E'$.

The preceding discussion applies to a BJT operated in a traditional, non-nuclear, electrical environment. When this environment is perturbed by significant neutron fluence, one can postulate that additional base current, say $\Delta I_B$, must be supplied in order to maintain the collector current at its pre-irradiated level. Let this base current enhancement be expressed as

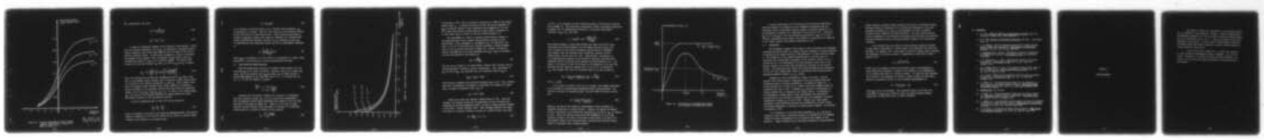
$$\Delta I_B = I_\phi \left[\varepsilon^{V_E'/V_{TE}} -1\right] + I_{\phi o} \left[\varepsilon^{V_E'/N_E V_{TE}} -1\right] , \tag{15}$$

where it is understood that $I_\phi$ is a function of the neutron energy imparted to the active region of the base-emitter junction. On the other hand, $I_{\phi o}$ is parametrically related to the neutron energy absorbed by the emitter sidewalls, the emitter-base depletion region, and the surface of the depleted layer associated with the base-emitter junction.

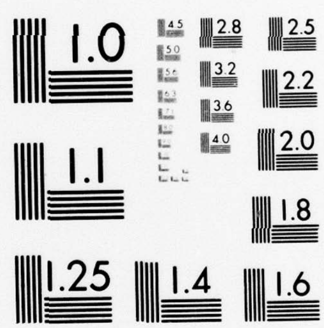
Clearly, the induced increment in base current can be modeled by incorporating two additional current sources in the base-emitter circuit of Figure (1). Current $I_{BEN}$ is placed in parallel with a source whose current is defined by the second term on the right hand side of (15), while the first term in this relationship is a diode in shunt with current $I_{BE}$ in Figure (1). Notice, however, that these modifications infer a mere redefinition of parameters $\beta_o$ and $I_{ER}$. Specifically, $\beta_o$ and $I_{ER}$ in the traditional model can be replaced by irradiated parameter values, $\beta_\phi$ and

AD-A062 790 TRW DEFENSE AND SPACE SYSTEMS GROUP REDONDO BEACH CALIF F/G 9/1
PROCESS-ORIENTED, HIGH-INJECTION CIRCUIT MODELS FOR INTEGRATED --ETC(U)
JAN 78 J CHOMA N00014-77-C-0043
UNCLASSIFIED TRW-78.4734.7-023-PT-2-VO NL

4 OF 4
AD
A062790



END
DATE
FILMED
3-79
DDC


1.0
4.5
5.0
5.6
6.3
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6

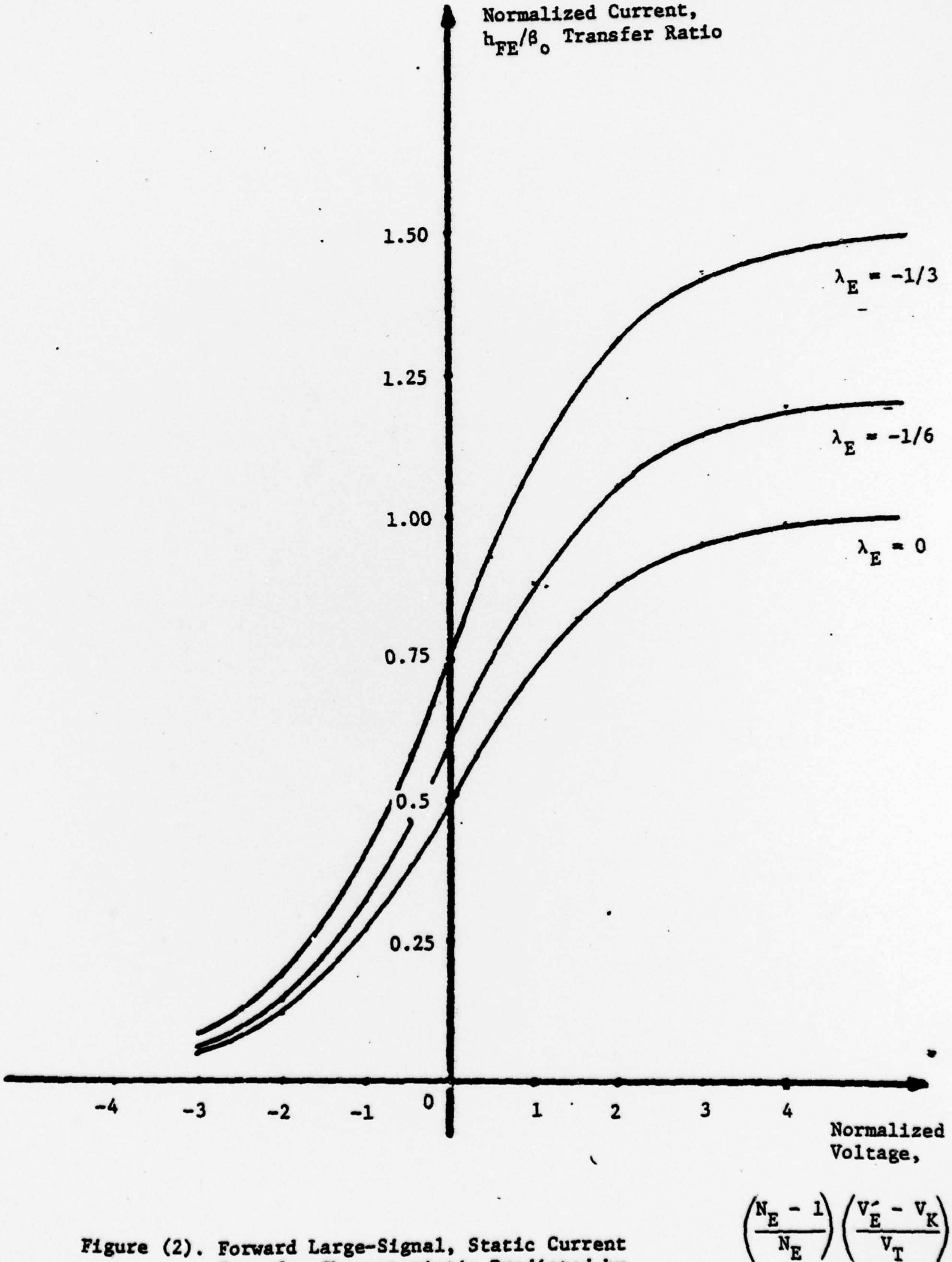



Figure (2). Forward Large-Signal, Static Current Transfer Characteristic Predicted by Model of Figure (1).

$I_{\phi R}$, respectively, such that

$$\beta_\phi = \frac{\beta_o}{1 + \beta_o I_\phi / I_S} \tag{16}$$

$$I_{\phi R} = I_{ER} + I_{\phi o}. \tag{17}$$

A number of noteworthy comments can be offered at this juncture. First, only two constant parameters, $I_\phi$ and $I_{\phi o}$, are required to establish neutron-induced changes in the current gain response over the range of very low-to-moderate injection levels. In particular, parameter $I_\phi$ serves to attenuate the maximum current transfer ratio at moderate current levels, while $I_{\phi o}$ influences the nature of $h_{FE}$ in low injection regimes. The latter point becomes clear when one replaces $I_{ER}$ and $\beta_o$ in (14) by $I_{\phi R}$ and $\beta_\phi$ to obtain

$$V_{K\phi} = V_K + \left(\frac{N_E}{N_E - 1}\right) V_{TE} \mathrm{Ln} \left[\frac{1 + I_{\phi o}/I_{ER}}{1 + \beta_o I_\phi / I_S}\right] . \tag{18}$$

Thus, the base-emitter junction bias commensurate with an $h_{FE}$ that is one-half of the maximum current transfer ratio at moderate current levels shifts as a function of the radiation parameters, $I_\phi$ and $I_{\phi o}$. Note, however, that while the maximum current transfer ratio always decreases in response to neutron irradiation, the half-gain junction bias level does not necessarily change, since if $I_{\phi o}/I_{ER} = \beta_o I_\phi / I_S$, $V_{K\phi} \equiv V_K$. In effect, the voltage change, $V_{K\phi} - V_K$, monitors the relative deposition of energy between the active and inactive portions of the base-emitter junction.

A second interesting point is that (16) can be written as

$$\frac{1}{\beta_\phi} = \frac{1}{\beta_o} + \frac{I_\phi}{I_S} , \tag{19}$$

which is precisely of the form of the classical Messenger-Spratt relationship. Indeed, a comparison of (1) and (19) infers the $I_\phi$ relates to neutron damage constant $K_\phi$ and fluence $\Phi$ in accordance with

$$I_\phi = K_\phi \tau_{FO} I_S{}^\Phi . \tag{20}$$

It is critical to note that since $I_\phi$ is a constant model parameter, $\tau_{FO}$ is necessarily a constant. This is to say that $\tau_{FO}$ is the minority carrier transit time across a field-neutral base. Since a field-neutral base is ensured at moderate currents only under the condition of a strongly back-biased collector-base junction, and since $\tau_{FO}$ is inversely proportional to common-emitter gain bandwidth product $f_T$, (20) is meaningfully expressed as

$$I_\phi = \left( \frac{K_\phi}{2\pi f_{TMAX}} \right) I_S{}^\Phi , \tag{21}$$

where $f_{TMAX}$ is understood to be the value of $f_T$ appropriate to linear active operation of a BJT subjected to strong collector-base back bias.

4.0 HIGH-INJECTION CHARACTERISTICS

When the base-emitter junction is strongly forward biased, the term involving $Q_{FN}$ in (9) cannot be ignored. Moreover, since $N_E$ is larger than unity, $I_{BE}$ is much greater than $I_{BEN}$ and thus, the net base current is closely approximated by the right hand side of (7). It follows that for $V_C' << 0$, (7) and (9) combine to produce

$$\frac{h_{FE}}{\beta_o} \simeq \frac{1}{(1 + \lambda_E) + \dfrac{Q_{FN} I_C}{I_S}} . \tag{22}$$

Equation (22) is plotted in Figure (3), wherein it is understood that zero collector current ($I_C = 0$) is in one-to-one correspondence with the moderate current levels associated with regions on the far right hand side in the graph of Figure (2). Observe in (22) that the high-injection current transfer ratio attenuates to one-half of its moderate current value at a collector current, say $I_K$, given by

$$I_K = \frac{(1 + \lambda_E) Q_{BO}}{\tau_F} . \tag{23}$$

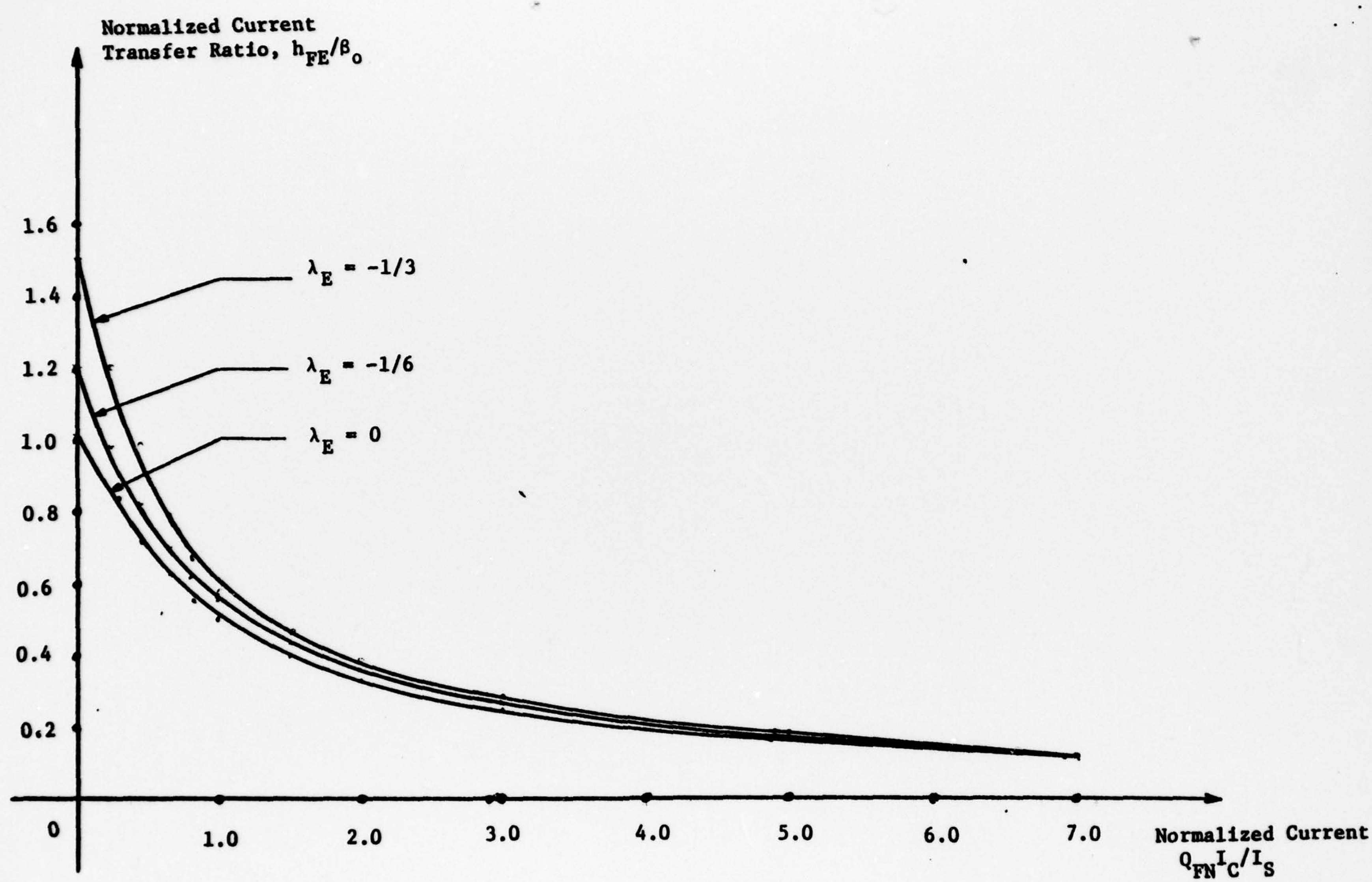



Figure (3). Forward Current Transfer Ratio At High-Injection Levels.

In arriving at (23), (10) is utilized to express $I_K$ in terms of base region transit time, $\tau_F$. It should be pointed out that the actual dependence of $h_{FE}$ on collector current is more complicated than suggested by (22) and (23), since base pushout at high-injection levels incurs a dependence of $\tau_F$ (and hence, $Q_{FN}$) on current $I_C$ and the voltage parameter, $\lambda_E$.

The development of a model to simulate neutron-induced changes in the high-injection current transfer characteristics derives from two observations. First, parameter $\beta_o$ attenuates to $\beta_\phi$, as defined by (16). Thus, $\beta_o$ in (22) is replaced by $\beta_\phi$, thereby incurring a uniform downward shift in the $h_{FE}$ curves portrayed in Figure (3). Second, the majority carrier concentration in the base decreases from $Q_{BO}$ to $Q_{B\phi}$ in accordance with the semi-empirical relationship [9]

$$Q_{B\phi} = \frac{Q_{BO}}{1 + K_B\Phi} , \tag{24}$$

where $K_B$ can be thought of as charge damage constant which reflects neutron-induced decreases in majority carrier concentration. Upon replacement of $Q_{BO}$ in (10) by $Q_{B\phi}$, one concludes that the irradiated value of $Q_{FN}$ is

$$Q_{FN\phi} = Q_{FN}(1 + K_B\Phi), \tag{25}$$

which directly supplants pre-irradiated parameter $Q_{FN}$ in (22). Note, however, that such a replacement of variables is equivalent to allowing the transit time to assume an irradiated value, $\tau_{F\phi}$, of

$$\tau_{F\phi} = \tau_F(1 + K_B\Phi). \tag{26}$$

There are at least two important ramifications of (26). First and foremost, the equation allows for the simulation of neutron-induced perturbations in the gain-bandwidth product, as well as neutron-induced changes in the forward current transfer ratio. This statement exploits the simple fact that for collector currents in excess of a critical value, say $I_O(V_C^*)$,

$$f_T = \frac{1}{2\pi\tau_F} , \; I_C > I_O. \tag{27}$$

In (27), $\tau_F$ is a function of both collector current $I_C$ and collector junction bias voltage, $V_C^*$. This functional relationship, which is portrayed graphically by Figure (4), is mathematically defined by a so-called "base-pushout function," $B_F(I_C, V_C^*)$, such that

$$\tau_F = \tau_{FO} B_F(I_C, V_C^*) = \frac{B_F(I_C, V_C^*)}{2\pi f_{TMAX}} . \tag{28}$$

The current parameter, $I_O(V_C^*)$ which defines the onset of BJT entry into high-injection operating regimes, and the pushout function, $B_F(I_C, V_C^*)$, can be related to such device processing characteristics as epitaxial layer doping, base and epitaxial layer geometries, minority carrier diffusivities, and the like [8], [10]. Alternatively, the behavior of $\tau_F$ in high-injection domains can be modeled by empirical equations whose parameters derive conveniently from measured $f_T$-characteristics [11]. The upshot of the matter is that (26) allows for the simulation of $f_T$ over both moderate and high injection regimes since if $\tau_F$ in (27) is replaced by $\tau_{F\phi}$, (26) through (28) infer an irradiated value of $f_T$ that is given by

$$f_{T\phi} = \frac{1}{2\pi\tau_{FO}(1 + K_B\Phi)B_F(I_C, V_C^*)} = \frac{f_T}{1 + K_B\Phi} , \tag{29}$$

for $I_C > I_O(V_C^*)$.

It is useful to interject that for $I_C \leq I_O(V_C^*)$, (26) remains applicable to the problem of simulating gain-bandwidth product characteristics. For collector currents not exceeding $I_O(V_C^*)$, the base pushout function is unity and

$$f_T \approx \frac{1}{2\pi[\tau_{FO} + V_{TE}C_T/I_C]} , \tag{30}$$

where $C_T$, the sum of the transition capacitances of both junctions, is nominally insensitive to neutron fluence. Clearly, the neutron irradiated value of low-current $f_T$ is obtained by replacing $\tau_{FO}$ in (30) by $\tau_{F\phi}$, as defined by (26). Unlike the uniform neutron-incurred degradation of $f_T$ at high collector currents, the effect of neutrons on low-current $f_T$ is seen to be non-uniform, owing to the relatively small influence which neutron fluence exerts on transition layer storage dynamics.

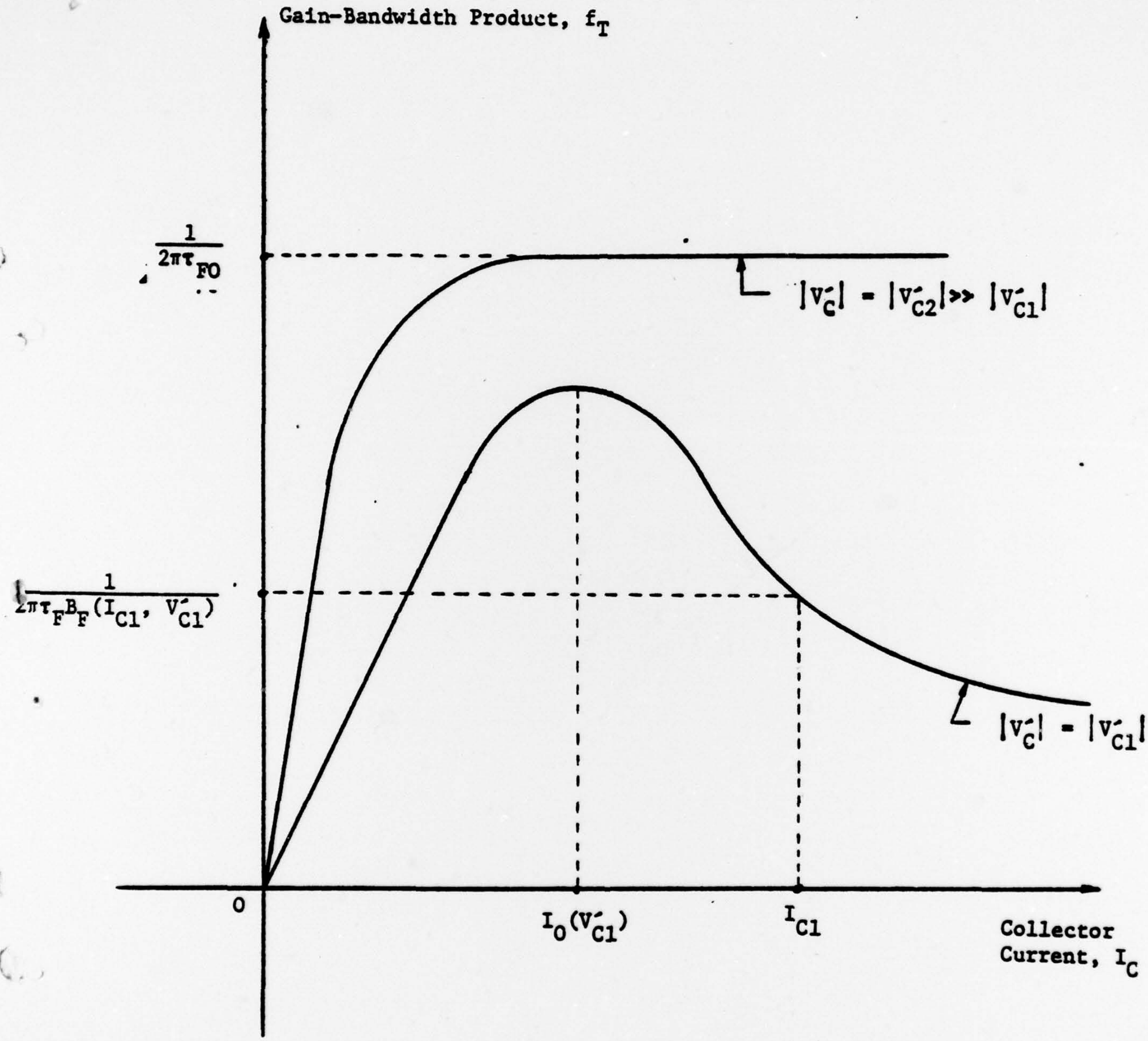



**Figure (4).** Common-Emitter Gain-Bandwidth Product as a Function of Voltage and Current.

A second ramification of (26) derives directly from the observation that this equation is predicated on the fundamental assumption that the irradiated value of base region majority charge is linearly related to its pre-irradiated counterpart by an expression of the form of (24). Since both $Q_{RN}$ in (11) and $Q_{FN}$ in (10) are inversely proportional to $Q_{BN}$, it is clear that the irradiated inverse transit time behaves in a manner that is identical to the forward transit time behavior prescribed by (26).

## 5.0 CONCLUSIONS

The fundamental premise of this paper is that an existing and reasonably accessible electrical model of a bipolar junction transistor is easily modified to incorporate the cognate effects of BJT exposure to a given neutron fluence, $\Phi$. The foundation for the required modifications is the fact that (1) additional base current must be supplied if the collector current of an irradiated BJT is to be maintained at its pre-irradiated value, and (2) the majority charge in the active base decreases in proportion to the neutron fluence. The additional base current and charge perturbation are stipulated by (15) and (24), respectively, which in turn define three neutron-related modeling parameters; namely, $I_\phi$, $I_{\phi o}$, and $K_B$.

Parameter $I_\phi$ can be determined in either of two ways. One way exploits (19), which entails a comparison of the pre-irradiated and post-irradiated values of the gain parameter $\beta_o$, as defined in Figure (2). A second technique is to relate $I_\phi$ to a known current gain damage constant in accordance with (20) or (21). Parameter $I_{\phi o}$ requires an investigation of current transfer ratio evidenced at low current levels. In particular, the base-emitter voltage (which closely approximates the base-emitter junction bias at low currents) is measured prior and subsequent to neutron irradiation to deduce $I_{\phi o}$ by way of (18). Finally, $K_B$ is most easily estimated by monitoring pre-irradiated and irradiated $f_T$ at fixed current and voltage appropriate to operation in high-injection regimes. The equation of interest is (29).

It is important to note that while parameters $I_\phi$, $I_{\phi o}$, and $K_B$ are constants, their correct utilization enables the simulation of the damaging effects of neutron bombardment over all forward active regimes of BJT operation. Indeed, parameter $K_B$ is ostensibly applicable to gain-bandwidth

product studies of bipolar devices operated in inverted or saturated regimes. Although inverse BJT operation is not specifically addressed in this work, parameters analogous to $I_\phi$ and $I_{\phi o}$ can presumably be found to simulate inverted current transfer ratio characteristics. The only problem inherent in this presumption is the difficulty encountered in monitoring pre-irradiated inverted performance without incurring permanent damage at the base-emitter interface.

It is believed that the theory of neutron effects modeling developed in this paper is applicable to a broad range of BJT simulation and prediction problems. For example, over a wide range of practical bipolar device operation, the dependence of collector current on temperature at fixed bias voltage is given by [12]

$$I_C = AT^M \varepsilon^{-V_{GO}/V_{TE}}, \qquad (31)$$

where $V_{GO}$ is the bandgap voltage and constants A and M are determined by device fabrication processes. Clearly, M is critical to the determination of the thermal sensitivity of collector current. It turns out that published data related to the dependence of minority carrier mobility on base region impurity concentration infers [2] that M behaves approximately as

$$M \simeq Ln(Q_{BO}/Q_{MO}) - M_O, \qquad (32)$$

where $Q_{MO}$ and $M_O$ are constants. The irradiated value of M evolves from replacement of $Q_{BO}$ by $Q_{B\phi}$, whence by (31), the neutron-induced thermal sensitivity of collector current is easily discerned.

## 6.0 REFERENCES


1. F. Larin, Radiation Effects in Semiconductor Devices, New York: John Wiley & Sons, Inc., 1968, Chapter 9.

2. S. M. Sze, Physics of Semiconductor Devices, New York: John Wiley & Sons, Inc.

3. J. S. Brugler, "Silicon Transistor Biasing for Linear Collector Current Temperature Dependence," IEEE Journal of Solid-State Circuits, Vol. SC-2, pp. 57-58, June 1967.

4. G. Messenger and J. Spratt, "The Effects of Neutron Irradiation on Germanium and Silicon," Proceedings of IRE, pp. 1038-1044, June 1958.

5. J. J. Ebers and J. L. Moll, "Large-Signal Behavior of Junction Transistors," Proceedings of IRE, Vol. 42, pp. 1761-1772, December 1954.

6. H. K. Gummel and H. C. Poon, "An Integral Charge-Control Model of Bipolar Transistors," Bell System Technical Journal, Vol. 49, pp. 115-120, May-June 1970.

7. J. M. Early, "Effects of Space-Charge Layer Widening In Junction Transistors," Proceedings of IRE, Vol. 40, pp. 1401-1406, November 1952.

8. J. Choma, Jr., "A Process-Oriented Model for the Simulation of Base Pushout In Integrated Bipolar Devices," IEEE Transactions on Electron Devices, Vol. ED-22, pp. 1079-1086, December 1975.

9. Reference #1, pp. 157-169.

10. J. Choma, Jr., "Process-Oriented, High-Injection Circuit Models for Integrated Bipolar Junction Transistors," ONR Final Report, No. N00014-75-C-1177, November 1976.

11. J. Choma, Jr., "A Curve-Fitted Circuits Model for Bipolar Transistor $f_T$ Roll-Off at High Injection Levels," IEEE Journal of Solid-State Circuits, Vol. SC-11, pp. 346-348, April 1976.

12. K. E. Kuijk, "A Precision Reference Voltage Source," IEEE Journal of Solid-State Circuits, Vol. SC-8, pp. 222-225, June 1973.

APPENDIX F

ACKNOWLEDGEMENTS

The number of people who contributed to this research project are too numerous to list herewith. However, I would be neglecting my professional obligations if I did not offer my personal congratulations for a job excellently done to Mr. E. J. Mock, who served as the senior engineer on this project. Mr. Mock almost single-handedly developed the PAREV program and worked diligently to ensure continuum among the various phases of this project.

I should also like to thank Mr. G. I. Haas, who supported Mr. Mock during the developmental phase of EQSOLVE. Last, but not least, I thank Mr. R. K. Ellis, the senior research engineer in my section, for bringing much needed experimental testing expertise to the program.